# Pneumatics Established

Francis Hauksbee and the air-pump

By

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## Abstract

This thesis is about the English air-pump and the instrument-maker Francis Hauksbee (1660-1713). I focus on the development, practice, and various applications of his air-pumps in the period from 1700 to 1745, and show how this led to establishing pneumatics as a distinct field.

I describe Hauksbee's background, and claim that his ability to build well-functioning air-pumps was due to his earlier career as a maker of commercial cupping-pumps and anatomical instruments. I show that his air-pumps were based on such devices; that his first version was a single-barrelled pump; and that it was this pump that gave him the reputation of being an outstanding instrument-maker. The celebrated double-barrelled pump, which came later, played no role in his early engagement with the Royal Society. I also argue that the air-pump became instrumentally black-boxed with Hauksbee's single-barrelled model, and reached its stabilized form with the double-barrelled one. Further, I argue that the various applications of Hauksbee's air-pump and air-pump accessories led to an extended vacuum-concept, where the pump became regarded as an unproblematic tool; and where 'vacuum' became thought of as an object. Moreover, I discuss the various activities of Hauksbee and his followers, and show that they can be seen as a separate group of instrument-makers, which I describe as the 'Pneumaticians'. This group took part in public lecturing and supplied instruments to individuals who performed air-pump experiments at home, and I claim that a private market for air-pumps and air-pump accessories had formed in London already before 1720. Finally, and contradictory to modern opinions, I argue that the air-pump in this period was not used for demonstrations of known facts only, but also for basic and applied research, and as a manufacturing tool as well.

I show that all these activities contributed to form pneumatics into an established area within natural philosophy, to a state where it held its own accepted methods, terminology, literature, instruments, and craftsmen.

Submitted for the Degree of Doctor of Philosophy
Hilary Term 2006

## Long abstract

This thesis is about the English air-pump and the instrument-maker Francis Hauksbee (1660-1713). I focus on the development, function, and various applications of his air-pumps in the period from 1700 to 1745, and show how this led to establishing pneumatics as a distinct field.

I describe Hauksbee's background, and claim that his ability to build well-functioning air-pumps was due to his earlier career as a maker of commercial cupping-pumps and anatomical instruments. I show that his air-pumps were based on such devices; that his first version was a single-barrelled pump; and that it was this pump that gave him the reputation of being an outstanding instrument-maker. The celebrated double-barrelled pump, which came later, played no role in his early engagement with the Royal Society. I also argue that the air-pump became instrumentally black-boxed with Hauksbee's single-barrelled model, and reached its stabilized form with the double-barrelled one. Further, I argue that the various applications of Hauksbee's air-pump and air-pump accessories led to an extended vacuum-concept, where the pump became regarded as an unproblematic tool; and where 'vacuum' became thought of as an object. Moreover, I discuss the various activities of Hauksbee and his followers, and show that they can be seen as a separate group of instrument-makers, which I describe as the 'Pneumaticians'. This group took part in public lecturing and supplied instruments to individuals who performed air-pump experiments at home, and I claim that a private market for air-pumps and air-pump accessories had formed in London already before 1720. Finally, and contradictory to modern opinions, I argue that the air-pump in this period was not used for demonstrations of known facts only, but also for basic and applied research, and as a manufacturing tool as well. I show that all these activities contributed to form pneumatics into an established area within natural philosophy, to a state where it held its own accepted methods, terminology, literature, instruments, and craftsmen.

In my work, I draw upon Hauksbee's book, *Physico-Mechanical Experiments on Various Subjects* from 1709 (second edition 1719); his articles in the *Philosophical Transactions*; the 'Journal Book' of The Royal Society, newspaper advertisements, lecture-syllabuses and other sources. The materials found in the archives of the Royal Society and in newspapers have in Hauksbee's case not been fully appreciated by previous historians. In addition, there exists a rich secondary literature on these problems. I will also use my experiences achieved by replicating one of his instruments, namely the rotating globe machine.

The thesis is organised in two parts. In Part 1, *Making the air-pump* (Chapter 1-3), I discuss the development of Hauksbee's air-pumps and air-pump accessories, and show how this created the technological basis for establishing pneumatics as an appreciated and useful subject. This material will be applied in Part 2, *Using the air-pump* (Chapter 4-6), where I discuss various applications of the pump and use them to explain how the transition from Boyle to Wright, and as well as further progress, became possible. There is a short summary after each chapter, recounting the most important findings and arguments.

In **Chapter 1** I argue that Hauksbee's competence as an exceptional air-pump maker was developed between 1699 and 1703, as a result of his experiences with construction and manufacturing of cupping glasses. Cupping and blood-letting was a much-used remedy for a series of illnesses at the time, and Hauksbee's cupping utensils contained a new design, where syringes were used to evacuate the glasses, instead of the traditional way by fire or mouth suction. I demonstrate that these syringes, which in fact were small air-pumps, became perfected between 1699 and 1701 in attempts to satisfy the customers.

I further show how a larger syringe, introduced in 1701, served as a transition from the cupping syringe to his first air-pump for use in natural philosophy. This syringe was described as a 'combined engine', which could serve as both an air-pump; a condensing engine for compressing air; and as a syringe for injecting air, wax, or mercury into pathological specimens.

Hauksbee's engagement in anatomy has until now been unknown. I describe his injecting instruments and argue that there was one important connection between these instruments, the cupping utensils and the air-pump. This was a valve: a reliable, uni-directional, self-closing contrivance originally developed for use with cupping utensils. The device became crucial for Hauksbee's most important instruments in medicine and natural philosophy,

**Chapter 2** is a survey of Hauksbee's first air-pump. Such a review is vital for understanding Hauksbee's air-pumps generally, and how his early model provided a background for further development, practice, and various applications of air-pumps and pneumatics.

The earliest evidence I have found of an air-pump with two barrels by Hauksbee is from May 1705. I therefore argue that the pump he demonstrated at the Royal Society in December 1703 was *not* the classic, double-barrelled one, as has normally been assumed, but another, until now unidentified, type. I argue that this was the single-barrelled model, introduced in 1701 as a further development of the combined engine. I then assess several contemporary appraisals of Hauksbee's 'improved' air-pump and show that they were all directed towards this smaller version, and not to the classic one, as assumed by all modern commentators. Westfall has stated that 'no one has been able to specify what Hauksbee's improvements of the air-pump in fact consisted in'. I answer this question here by comparing Hauksbee's single-barrelled pump with earlier air-pumps by Boyle, Hooke and Papin, and using Hauksbee's own concepts like 'ease' and 'exactness'. I demonstrate that these terms alluded to easy and convenient leak-tightening and handling of the receiver, exact pressure-measurements by an in-built barometer; and to an air-inlet function of this pump. Further, I show that, at this stage, Hauksbee had developed a series of air-pump accessories for use in experimental philosophy.

Based on this evidence, I finally argue that these issues contributed to facilitate convenient and reproducible experiments, and thus constituted a preliminary background for the circumstances depicted by Joseph Wright.

The well-known, classic, double-barrelled air-pump is often thought of as Hauksbee's most important instrument. In **Chapter 3** I raise serious doubts about this perception. I examine the technical dissimilarities between the two models, and although the classic one was a beautiful, well functioning masterpiece that might have had social consequences for Hauksbee personally, I show that the difference it

could make on scientific practice could not have been very large. I further argue that the leap from Boyle's and Papin's pumps to Hauksbee's smaller, single-barrelled model was much greater and more important than the step from his single to his double-barrelled one.

The new pump was announced in the newspapers, but I have found no direct evidence of this change of technology elsewhere in the written material. It is also evident that Hauksbee seldom mentioned the air-pump explicitly in the experimental records. I use the lack of information here as a starting point to discuss technical, scientific and social aspects of the air-pumps. The concept of black-boxing is important here, and I claim that Hauksbee, even in his single-barrelled model, managed to perfect the air-pump to a level where it no longer needed much attention or explanation in texts. It was thus ready for settings like Wright's, where the effects were the essential and the operation a routine.

Finally, I argue that the air-pump reached its 'stabilized form' with Hauksbee's double-barrelled model, a pump-concept that lasted to the twentieth century.

**Chapter 4** is about the different stages of development and use of the air-pump by Hauksbee and other practitioners. I first show how attention moved away from the pump itself and towards external instrumentation. It becomes clear that the air-pump developed from a state where the pump-cylinder and the receiver were integrated in one unit through pumps with separate barrels and receivers, to pumps using a series of specialized receivers. Further, I discuss how experiments and demonstrations were performed at this stage, giving examples on animal-tests, glass-breaking, and the firing of gunpowder in the vacuum inside such purpose-made receivers. Here I show that these experiments contributed to popularise the vacuum-concept through visualization and illustrated concepts involving phenomena regarding pressure, spring and weight of air.

I also show that the air-pump developed further, to a stage where pump-accessories came to be regarded as more significant than the pump itself. I exemplify this by discussing a few of Hauksbee's instruments, the rotating globes and cylinders, and a hollow prism, all of which could be evacuated by the pump. From this I claim that the air-pump here had become downgraded to a supplier of vacuum only, with no other purposes in the experiments.

Finally, I argue that the various applications of Hauksbee's air-pump and air-pump accessories brought pneumatics to a state where the pump became regarded as a black-boxed and unproblematic tool; and where *vacuum* became thought of and handled as an object.

In **Chapter 5** I discuss how the application-area of the air-pump expanded during the first half of the eighteenth century, from being an important philosophical instrument available to only a small group, to a publicly accessible device for use in public and private demonstrations. According to Stewart, the experiments that were shown at public lectures in London during this period served as practical counterparts to the queries in Newton's *Opticks*, and were together crucial for disseminating natural philosophy and Newtonianism. I discuss the role of pneumatics in this undertaking, and show that, for example, basic properties like pressure, spring and omni-directionality of atmospheric air were made familiar to the public through cupping-related experiments. I also show that a private market for air-pumps, air-pump accessories and technical literature had developed by 1720, claiming that one reason was the improved quality of the

instruments. The equipment had become handy and reliable, as well as easily available, which facilitated settings like Wright's. Further I argue that all these activities contributed to transform pneumatics into an established field within natural philosophy, to a subject with its own accepted methods, terminology, literature, instruments and craftsmen.

Hauksbee had apprentices and other associates who were engaged in the production of pneumatic instruments. I discuss how this activity, conducted by a few practitioners, evolved into a profession. Further I show that Hauksbee and his followers formed a small group of instrument-makers that was active in London up until about 1745, and operated separately and independently of the optical, mathematical and philosophical instrument-makers. In addition to manufacturing air-pumps and other pneumatical instruments as well as medical utensils, most of them were also engaged in public lecturing on natural philosophy. I denote this group as the 'Pneumaticians'.

The focus in **Chapter 6** is about research by air-pumps and goes beyond the Wright-image. The number of natural philosophers who performed novel investigations with the air-pump in this period is said to be very small. Francis Hauksbee's own work on static electricity has been mentioned as the only exception of such an activity. However, the air-pump *was* used for research in this period, in addition to the usual demonstrations. I show this by discussing Stephen Hales' use of the device for investigations on plants, animals, and the air – where it acted as a rather obscure research instrument. Further I discuss Alexander Monro's activities of preparing pathological specimens, and show how the air-pump became used as merely a manufacturing tool. The air-pump as a practical tool is definitely *not* included in the modern characteristics of the seventeenth and eighteenth century air-pump. From this I argue that pneumatics had developed even further, to yet another stage, where it served as a supporting agency for other sciences.

The aim is to show that the air-pump had now (ca 1745) approached a level of versatility where it functioned as an unproblematic tool and method, where both the instruments and theories in pneumatics were regarded as fully accepted and 'black boxed' by practitioners working in other fields. Pneumatics was established and had become absorbed into larger realms, both theoretically, and practically.

The replication process of Hauksbee's rotating globe machine, including methodological considerations of such undertakings, is discussed in the **Appendix.**

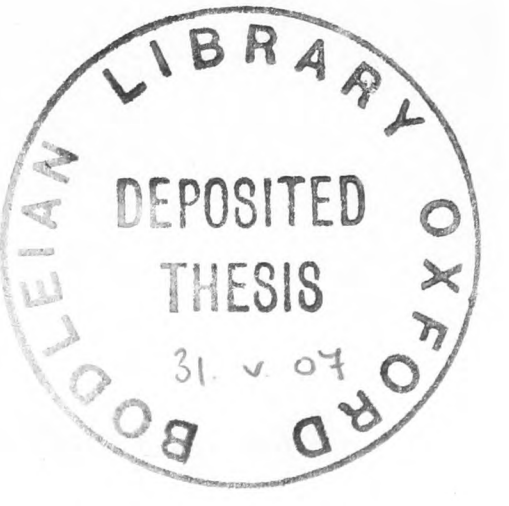
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**For my wife**

# Preface

This thesis, 'Pneumatics Established', is about the English air-pump and the instrument-maker Francis Hauksbee (1660-1713). I focus particularly on development, practice, and various applications of his air-pumps between 1700 and 1745, and how this led to establishing pneumatics as a distinct field.

The air-pump of the previous century is well-known from Shapin and Schaffer's book *Leviathan and the Air-Pump* of 1985. However, this account from Boyle and Hobbes's period has contributed to shape a general impression of early air-pumps as temperamental and unreliable devices, whereas I argue this only to be true for the first generation of English air-pumps (Boyle's). The second generation, dominated by Hauksbee's pumps, was of a very different character, and I explain why. If *Leviathan and the air-pump* can be said to represent the first chapter in the history of the English air-pump, this study holds material for the second.

Historians of science have variously described Hauksbee as an experimenter, natural philosopher, public lecturer, as well as an instrument-maker. These studies have often emphasised his attempts to explain electric phenomena, or his role as a demonstrator in the Royal Society, and in the public lectures on natural philosophy that were given in London at the time. His background has been described as a 'mystery'. Until now, his first known public appearance has been at a Royal Society meeting in December 1703, where he presented and performed some experiments with an air-pump. The lack of information on his previous activities, especially on where he had learned to make his highly efficient double-barrelled air-pump, has led to numerous speculations – for example that he might have been an assistant to Robert Boyle.

In this thesis, I seek to dispel the 'mystery' of Hauksbee and shed light on his background. I claim that his ability to build these high-quality air-pumps was due to his career as a producer of commercial cupping-pumps and anatomical instruments, and without any decisive connection to Boyle's. Hauksbee made and sold various cupping-utensils from at least 1699, and his first air-pump, a single-barrelled model introduced in 1702, was modelled on such technology. This pump possessed all the important qualities that characterized his later model and was the one which gave him the reputation of being an outstanding instrument-maker. It was also this pump that Hauksbee demonstrated at his first performance in the Royal Society. Furthermore, I argue, contrary to modern opinions, that the well-known, classic double-barrelled air-pump made little impact at the time. It was introduced in 1705 and played, for example, no role in Hauksbee's early engagement with the Royal Society.

The concept of 'black-boxing' is central in this study. I show that while the air-pump had become conceptually black-boxed by Boyle (which means that it had become commonly accepted as an instrument that could produce new matters of fact), the instrumental part of the process took place with Hauksbee's single-barrelled model. Hauksbee's contribution was to convert it into a reliable and user-friendly instrument, with attention directed to what the pump could do, not to how it worked. Further, I argue that the air-pump reached its 'stabilized form' with the double-barrelled one, a pump-principle that, with small variations, was used into the twentieth century. The various applications of Hauksbee's black-boxed air-pumps and air-pump accessories led in turn to an extended vacuum-concept, where the pump became regarded as an unproblematic tool and where 'vacuum' became thought of as an object.

Hauksbee was not recognised as a natural philosopher by his contemporaries, nor did he name himself as any particular kind of an instrument-maker. On the other hand, he gave public lectures on natural philosophy, and made and sold air-pumps, cupping-utensils and instruments for making pathological specimens. He also published fifty articles on natural philosophy in the *Philosophical Transactions*. Who was he? By studying all his instruments, those used in the public lectures and those made for sale, it becomes clear that he manufactured mainly such ones that worked from the principle of rarefying and condensing air. Hauksbee had several apprentices and associates that followed him, and a study of their activities shows a similar pattern. I argue that this group can be seen as a small, distinct and separate group of instrument-makers that were active in London until about 1745, and I describe them as the 'Pneumaticians'. Characteristics of this group were the production and sale of air-pumps, air-pump accessories, condensing engines, cupping-utensils and anatomical instruments. They took part in public lecturing and most had connections to the Royal Society. Further, they also supplied instruments to individuals who performed air-pump experiments at home, and I

claim that a private market for air-pumps and air-pump accessories had formed in London already before 1720.

The air-pump has mainly been seen as an instrument for demonstrations of known facts in this period. However, I show that the pump became used in basic and applied research, and also as a manufacturing device at the time, and thus used for utilitarian purposes. I make this clear by discussing a few applications of the pump in contemporary research on botany and zoology, as well a tool for making pathological specimens. Here, pneumatics had become a supporting agency to other disciplines. All these activities contributed to establishing pneumatics as an area within natural philosophy, complete with its own accepted methods, terminology, literature, instruments, and craftsmen.

An analysis of this 'second generation' of air-pumps is important because it offers a complement to the standard history of the pump. Further, it sheds light on even broader issues in the study of eighteenth-century science, such as the relationship between surgical and philosophical instrument making, the 'black-boxing' of methods, hypotheses and instruments, cooperation between instrument-makers and natural philosophers, and the social status of the instrument-maker.

My approach is different from that of, for example, Shapin and Schaffer's. I start off by focusing on technical aspects of the subject, which in turn leads me into social issues of natural philosophy in the period.

Much of my fascination for air-pumps and Francis Hauksbee can be explained by my own background. Working as a technician at a plasma-physics laboratory at the University of Tromsø, Norway for more than 20 years, I found many of his activities surprisingly familiar. Some of my specialities in the lab were vacuum technology, high power technology and electronics, and by studying Hauksbee's engagements with air-pumps and electricity, I felt I got right to the very beginning of these subjects.[1] Another parallel was our studies of plasmas and ionized gases, and Hauksbee's productions of luminous phenomena in vacuum. Yet another aspect was my engagement as a technician working for scientists and graduate students, and Hauksbee's engagement with the Royal Society and natural philosophers. Many of my responsibilities consisted in building scientific instruments and preparing experiments, as well as writing instruction manuals and technical reports; undertakings not unlike Hauksbee's.

My interest in history of science started in 1992, when I restored a large vacuum-chamber for aurora-simulations, built by the Norwegian physicist Kristian Birkeland (1867-1917).[2] By continuing further backwards in time, to Hauksbee's

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[1] T. Brundtland, 'A description of the vacuum chamber for the Blaaman plasma experiment'. *Vacuum.* (Pergamon Press), vol. 43 no. 3 (March 1992), 185-7. The term 'air-pump', describing a device for creating a sub-atmospheric pressure, is today replaced with the term 'vacuum-pump'.

[2] T. Brundtland, *The laboratory work of professor Kristian Birkeland* (Tromsø, 1997).

period in the early eighteenth century, I have in fact been studying the history of my own profession: instrument-making in an experimental, academic setting.

I first learned about Hauksbee when I did an M.Sc. course in 1997/8 entitled 'History of Science: Instruments, Museums, Science, Technology' at the Museum of the History of Science in Oxford. The fact that modern texts portrayed him as an excellent instrument-maker who suddenly appeared at the Royal Society in 1703 with a brilliant air-pump, but with a background totally in the dark, caught my fascination at an early stage. That nobody today could explain where he had learned to build his air-pumps, and where and how he got acquainted with electricity and natural philosophy became more and more of an obsession to me, especially when I started to read various attempts to solve the mystery.

Despite the above, the present work is not about my affiliation with Hauksbee or a comparison of new versus old technologies. Neither is it an assessment of early experimental practice from the perspective of modern physics. It is rather an attempt to understand Hauksbee's air-pumps and their applications in their own context, seen from the position of an historian of science taking a technical approach.

I draw upon Hauksbee's book, *Physico-Mechanical Experiments on Various Subjects* from 1709 and 1719 (second edition); his articles in the *Philosophical Transactions*; the 'Journal Book' of The Royal Society, newspaper-advertisements, lecture-syllabuses, and other sources. The materials found in the archives of the Royal Society and in newspapers have in Hauksbee's case not been fully appreciated by historians. In addition, there exists a rich secondary literature on these problems. I will also use my experience gained in replicating one of his instruments, the rotating globe machine.

# Acknowledgements

Many thanks to my patient supervisors Dr. Stephen Johnston and Professor Robert Fox for all their help and support in my efforts to convert from a university-technician to an historian of science.

Thanks also to my housemates in 11 Norham Gardens for making me feel at home in Oxford. Thanks to Shlomi Segall for helpfully commenting on my early drafts and proposals.

Further, thanks to Narve Fulsås and Kristoffer Rypdal at University of Tromsø, Norway, for interesting and helpful discussions during my research, and to Hans Pecseli and Jan Trulsen at University of Oslo, Norway, for reading the thesis-draft. Thanks to John Peter Collett at Forum for University History, University of Oslo for many helpful suggestions about text and content. Thanks to Stephen D. Snobelen, University of King's College Halifax, for letting me use his 'Archive of early eighteenth century science advertisements'.

Also: many thanks to Nick Pierpan and to Miranda Hodgson for proofreading the manuscript.

This project is mainly self-financed, but with contributions from the University of Tromsø and from the Forum for University History, University of Oslo.

Finally, but most important of all, thanks to my wife and my family in Norway for letting me embark on this long and difficult, but very interesting and rewarding journey towards my D.Phil.

The length of this thesis, including abstracts and captions but excluding the Bibliography is 97000 words.

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# Abbreviations

| | |
|---|---|
| *BJHS* | *British Journal of the History of Science.* |
| *Boyle's Works* | M. Hunter and E. Davis (eds.), *The Works of Robert Boyle* (14 vols, London, 1999). |
| *DSB* | *Dictionary of Scientific Biography.* |
| *ODNB* | H.C.G. Matthew, B. Harrison and L. Goldman (eds.) *Oxford Dictionary of National Biography* (Oxford, 2004). |
| JJC | The John Johnson Collection, Bodleian Library, Oxford. |
| *PME* | F. Hauksbee, *Physico-Mechanical Experiments* (London,1719). |
| *PT* | *Philosophical Transactions of the Royal Society of London* (London, 1665 -1760). |

Dates are giving according to the new style.

Some newspapers in the period were issued with dates covering several days, for example 2-5 January 1701. Reference is made to them for their first day of publication (2 Jan 1701).

All the cited newspapers were published in London.

Francis Hauksbee 'Senior', or 'the elder', is Francis Hauksbee, born in Colchester 1660, died in London 1713.

Francis Hauksbee 'Junior', or 'the younger,' is Francis Hauksbee, born in London 1688, died in London 1763. He was a nephew of Francis Hauksbee the elder.

# Introduction

A famous and much-appreciated painting in the National Gallery in London is Joseph Wright's *An Experiment on a bird in the Air Pump* from 1768. It depicts the device in one of its most common applications at the time: rational entertainment and education, here shown in a domestic setting.

The scene is rather dramatic; it shows a dying cockatoo in the evacuated glass-receiver of the pump and the reactions of the on-lookers. See Figure 1. Some react with grief and horror, like the two girls, in seeing the rare and exquisite creature lying helpless and gasping for air in the container while their father seems to comfort them with logical explanations.[3] The boy in the right corner lowers the bird's cage, probably attempting to move the experimenter to advance the release of the bird. The young man to the left shows no such emotions, expressing a rational attitude by timing the experiment with a stopwatch. In the middle of the painting, behind the pump, is the experimenter himself, depicted here almost as the Almighty: a figure who by a gesture can decide over life and death by letting air back into the receiver and to the white bird. The elderly man sitting at the right is widely considered to be meditating on death, symbolized by the dying bird and what is believed to be a preserved human skull in the liquid-filled glass in front of him, lit from behind by a candle.[4] The only one who seems unaffected is the young lady at the right, only concerned with her neighbour.

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[3] E. Langmuir, *Visitor's Guide* (The National Gallery, London, 1997), 330.
[4] S. Daniels, *Joseph Wright* (London, 1998), 40.



**Figure 1.** *An Experiment on a bird in the Air pump.* Joseph Wright, 1768.

While this picture describes the air-pump as an instrument that can easily exhibit the active powers of Nature and inspire a corresponding human awe, there exists another picture of an air-pump with quite a different message. About one hundred years earlier, Robert Boyle (1627-1691) had published a book, *New Experiments Physico-Mechanical, touching the spring of the air,* describing forty-three experiments with an air-pump.[5] It contains an illustration of his first pump, surrounded by some detailed drawings of various mechanical components and pump accessories.[6] See Figure 2. Boyle's aim was to show a real air-pump; how it was constructed, and how it worked. It served as a supplement to his written accounts, where Boyle meticulously described every detail of his air-pump practice. This included technical and construction features of the pump, the applied materials like glass and sealing agents, problems during manufacturing, as well as the failures and successes of the experiments. Boyle's overall intention with his writings and illustrations was to make readers at other locations able to replicate his experiments, and thus confirm his own experimental results. It is clear that Boyle's air-pumps were difficult and temperamental instruments, subjected to

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[5] R. Boyle, *New Experiments Physico-Mechanical, touching the spring of the air* (London, 1660). The book is found in M. Hunter and E. Davis (eds.), *The Works of Robert Boyle* (14 vols, London, 1999) [*Boyle's Works*], i, 141-299.

[6] *Boyle's Works*, i, 156.

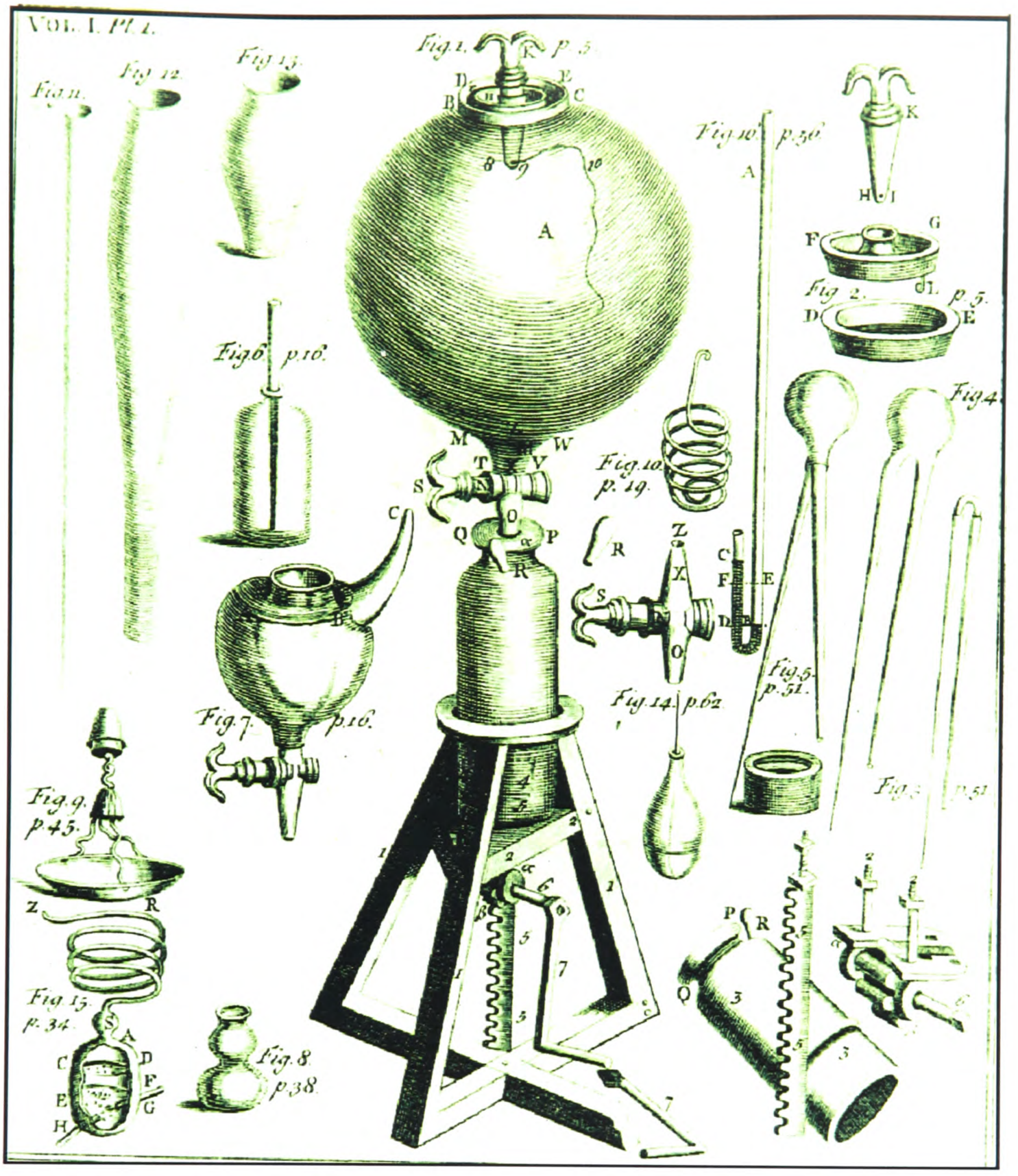



**Figure 2. Robert Boyle's first air-pump, 1659.**

constant rebuilding and maintenance. Doing experiments with them was a slow and cumbersome task and reliant on the constant presence of technicians.

Wright and Boyle's pictures were created at different times, for different purposes and with different conventions. The social context of Boyle's message was restricted, and his target group was a relatively small one, consisting mainly of natural philosophers in Britain and abroad. Wright was an artist addressing a different and larger audience. Despite this contrast, a comparison makes sense. The respective pumps have, for example, some clear resemblances to each other. The central component in both is the large spherical receiver that can be opened at the top for inserting objects. Both actors were concerned about experiments, but while

Wright tried to communicate the *effect*s of an air-pump experiment, Boyle's main concern was to tell others about *how to make one*. Most commentators on Wright's painting also focus on the emotions of excitement, anxiety and indifference among the onlookers, as well as the overall depiction of an experiment taking place in a private home. The air-pump as a technical device is generally left out of these interpretations. On the other hand, influential reviewers of Boyle have been particularly concerned about the air-pump itself, discussing the difficulties that he experienced in building, maintaining, operating, as well as documenting it. His efforts, including discussions with contemporary critics, contributed to establish a way to produce, express and spread knowledge obtained experimentally.[7]

By analysing the air-pump itself in Wright's painting, it is evident that it is not operated at the moment. No hand is moving the crank, but the receiver is depicted as evacuated (by the dying bird), signalling a leak-proof and carefree construction.[8] Boyle, on the other hand, particularly described such issues as problems, for example of making a leak-tight device that could be easily pumped:

> But Observing that the great difficulties men met with in making an Engine that would exhaust and keep out a Body so ponderous as the Atmosphere. The second model was only to some purposes better.[9]

The distance from Boyle to Wright seems immense. Even if there is a time span of more than hundred years between the two images, the effective time between the two situations is in fact much shorter. Boyle ended his experiments with air-pumps in the 1670s, but there are few signs of any further development of air-pumps in England before around 1700. Boyle's last experiments were performed in a double-barrelled pump made by Denis Papin (1647-1712), a pump substantially improved from Boyle's earlier models but clearly inferior in both efficiency and ease of operation to the one in Wright's painting. On the other hand, I have found indications that scenes similar to that depicted by Wright could have already taken place in London around 1720. How was the transition from Boyle to Wright possible?

The development of the air-pump in this period can be symbolized by yet another picture. In 1728, Stephen Hales (1677-1761) published a book called *Vegetable Staticks*, containing a series of accounts of experiments on plants and animals, some of them made by an air-pump. Here the pump was used for research, but the supplied illustration showed only the experiment, the air-pump was not depicted. See Figure 3.[10] This picture (and the accompanying text) was thus of a

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[7] 'The three technologies'. See: S. Shapin and S. Schaffer, *Leviathan and the air-pump* (Princeton, 1985), 25.

[8] None of the authors on Wright that I have consulted have commented on this fact.

[9] *Boyle's Works*, vi, 29-30.

[10] S. Hales, *Vegetable Staticks* (London, 1969), *Fig 32*. All references are to this edition. First published in London (1727).

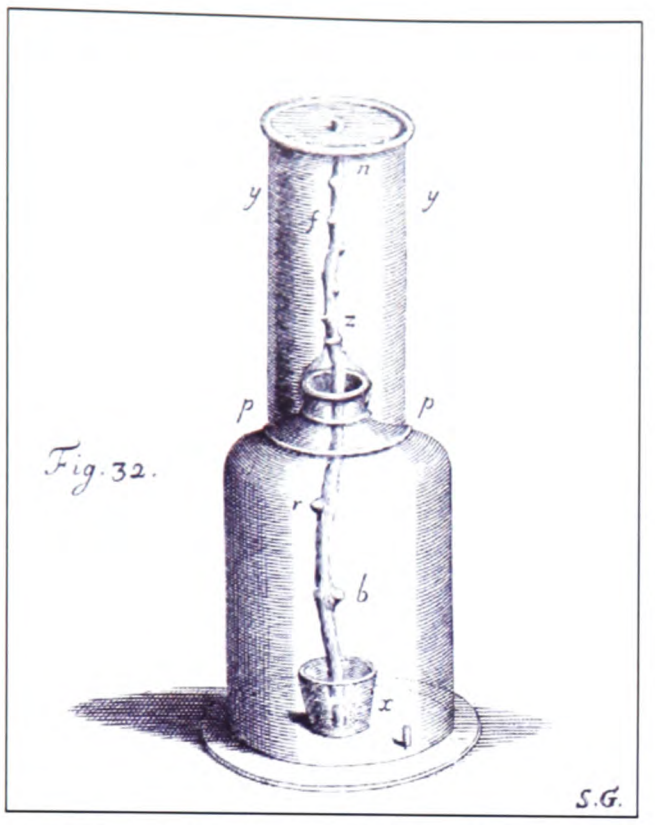



**Figure 3.** Stephen Hales's air-pump experiment (1727).
Where is the air-pump?

third kind, here addressing the learned community, for example members of the Royal Society, and only showing what was needed to understand the experiment. It is clear that while the air-pump in this period (as illustrated by Wright) had a visible and prominent status, there were other situations (as Hales's) where it had an important, but obscure role. Like Boyle, Hales used the air-pump for research but the pump was not emphasised at all in his illustrations and accounts. What had happened to the awareness of the pump in this case?

These are questions I seek to answer here. The period was characterized by great political, economical, social, technological and scientific developments.[11] The wider context of the situation given by Wright must have been set up by a variety of such factors, including the development of the air-pump as a reliable and 'user-friendly' instrument. For Hales, the use of the pump must have been a routine, as he emphasized other research objectives in his reports. One of my aims is to explain why English air-pump technology and air-pump practice could go from 'being difficult' to 'being easy', and further to become a routine during this relative short time period.

I argue that the key figure in this process was the instrument-maker Francis Hauksbee (1660-1713) and his engagement in pneumatics. The illustrations of Boyle's first air-pump and Wright's painting constitute the greater context of my study, but much of my discussion will be concentrated on issues between 1700 and 1745. 1700 is chosen as the start since Hauksbee was at that time beginning to advertise some air-pump related products in the London newspapers. I will finish around 1746, since this was the year when an air-pump by a English maker outside the Hauksbee-tradition can first be found.[12]

An important concept in this undertaking is *black-boxing*. The term 'black-box' is often used to describe an instrument whose elements or constituents are unknown or seen as irrelevant, but whose functions are understood. 'Black-boxing' is correspondingly used to describe the social process that an instrument undergoes from its initial status as a problematic, questioned and unreliable prototype, to its eventual approval as a well-functioning and accepted device. According to Trevor

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[11] L. Stewart, 'Philosophers in the counting-houses: commerce, coffee-houses and experiments in early modern London', in P. O'Brien, et al. (eds.), *Urban Achievement in Early Modern Europe* (Cambridge, 2001), 326-45.

[12] G. Adams, *Micrographia Illustrata* (London, 1746).

Pinch, the black-boxing of instruments are obtained when 'the social struggle over a piece of knowledge has become embedded in a piece of apparatus'.[13] In a wider sense, this also includes a process where manual skills, required to operate the instrument, become replaced by technology embedded in the newer versions, while the device itself becomes available to larger groups. It is also possible to distinguish between conceptual and instrumental black-boxing. Boyle's efforts to develop an air-pump that could produce matters of fact, and getting the air-pump accepted as such, was a process of conceptual black-boxing.[14] The instrumental aspect, which happened later, describes its development into a simple and convenient pump that worked without requiring much technical insight from the operator. I will also include the development of the corresponding discipline itself into this process, in this case 'pneumatics'. In this period, the term 'Pneumatics' was described as a 'Branch of Mechanics, which considers the Air in Motion with its Effect; but is more usually taken for the Doctrine of the air, or the Laws according to which that Fluid is condensed, rarefied, gravitates, etc'. Pneumatic experiments were those that were 'Made in the exhausted receiver of the air-pump'.[15] Another described air as 'an elastic and compressible fluid', and pneumatic engines (air-pumps) as 'all those instruments and machines that work by means of an elastic fluid'.[16] From being characterised by simple and unreliable instruments and difficult experiments of Boyle's period, a reputation that persisted up to around 1700, pneumatics then matured through a phase characterised by being a distinct subject in public lectures, and pump-making being a craft. This field grew so common and unproblematic that it not only became useful in other enquiries, but was even absorbed into other, larger disciplines, typified by Desaguliers's textbooks on natural philosophy (1734, 1744).[17]

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[13] T. Pinch, *Confronting Nature* (Dordrecht, 1986), 214.
[14] T. Nickles, 'Justification and experiment', in D. Gooding, et al (eds.), *The uses of experiment* (Cambridge, 1989) [Gooding (1989)], 311.
[15] J. Harris, *Lexicon Technicum*, 5th ed (London, 1736), under 'Pneumatic' and 'Pneumatical Experiments.'
[16] B. Worster, *A Compendious and Methodical Account* (London, 1722), 132, 150.
[17] See: J. Desaguliers, *A Course of Experimental Philosophy* (2 vols, London, 1734, 1744).

# 1. The classic image of the air-pump

## 1.1 Air-pump design

When Hauksbee entered the realm of the air-pump, the instrument had already been around for almost fifty years. Air-pumps had been made and used in Germany, Holland, France and Italy as well as England and had become an important instruments for natural philosophy. First contrived in 1647 by Otto von Guericke (1602-1686), the air-pump consisted of a syringe and a closed receiver connected by a system of self-closing valves, with most of the device submerged in water to prevent leaks. His original intention was to prove the existence of a vacuum, and not to create a space for undertaking experiments in the vacuum created.[18] Guericke wanted to refute Descartes' (1596-1650) cosmology and related ideas on space and matter, but also to use his pumps for political purposes, for example through the famous demonstration of the Magdeburg hemispheres. However, the overall contribution to the subsequent development of the air-pump as a scientific instrument was small.[19]

A quite different concept was used during the 1660s at the flourishing Accademia del Cimento of Florence, Italy.[20] This method was based on the Torricellian barometer and used the upper part of the tube as the experimental space. The classic Torricellian barometer consisted of a long glass tube that was closed in one end. When it became filled with mercury and turned upside down with one finger closing the open end, and this end was placed in a vessel filled with mercury, the mercury in the tube would drop down to a certain level when the finger was removed, creating an empty space above the mercury (the Torricellian void). The distance between the top of the mercury column in the tube and the mercury surface in the vessel was a measure of the weight of the atmosphere. Used as an air-pump, the top of the tube was simply enlarged into a bulb, and pumping was obtained by first filling the tube and the bulb with mercury, then closing a top-lid, letting the mercury drop down through the tube and into a basin, an action that created an empty space above the mercury. The main intention of this construction was, in contrast to Guericke's early air-pumps, to perform experiments. Experiments were also undertaken, ranging from studies of the behaviour of animals to the melting of snow in vacuum.

In England, Robert Boyle heard about Guericke's work and began to devise his own air-pump. His first functional model or 'Pneumatical Engine' was made by Robert Hooke (1635-1703) in 1659, and was to some extent like Guericke's, with a large syringe connected to a receiver through a stopcock. However, Boyle's aim was a machine that could produce an evacuated space that was suitable for experiments. Hooke also made a second model, while Papin made Boyle's third

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[18] A. C. van Helden, 'The Age of the Air-Pump', *Tractrix*, vol. 3 (1991), 151.
[19] Ibid, 152. Guericke published his work too late to get any influence.
[20] W. Middleton, *The Experimenters* (Baltimore, 1971).

pump (1676). See Figure 4. Papin had earlier been active with Christiaan Huygens in Holland in constructing air-pumps with which to perform experiments. Huygens had introduced the bell-shaped receiver, which made it much easier to prepare and perform experiments, a facility that soon became standard for later pumps, for example in Boyle's second model (1662).

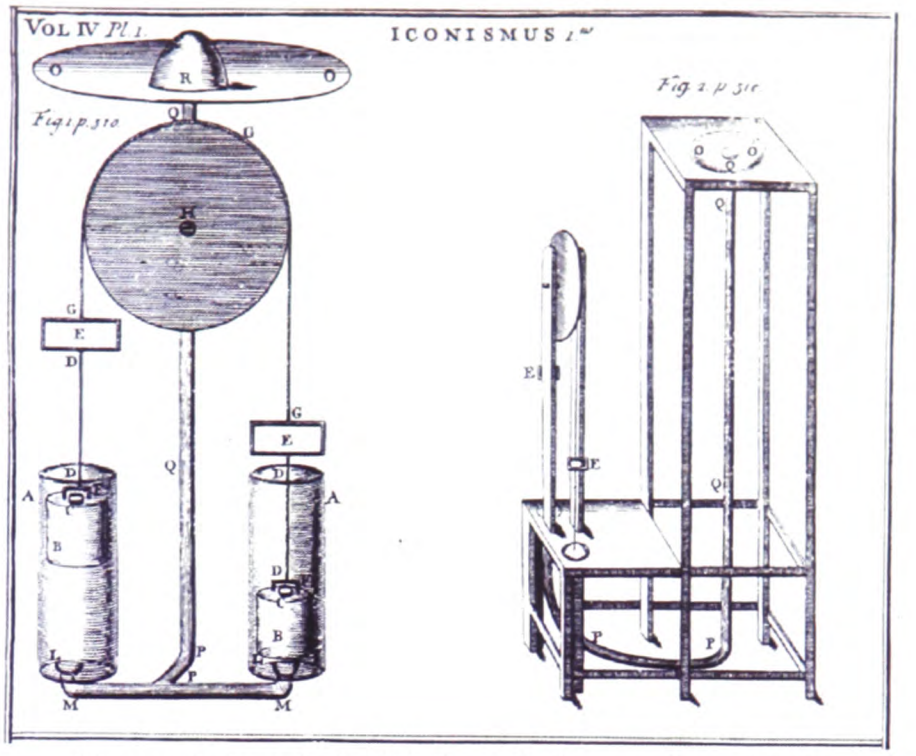



**Figure 4.** Papin's double-barrelled pump from 1676. Functional and perspective drawing.

However, the air-pumps and the pneumatic experiments of the seventeenth century did not settle the old, classical debate between the vacuists and the plenists on whether a vacuum could exist or not.[21] This question was not solved by air-pump experiments, but simply faded away with the old generation. Instead, Boyle used the pump to answer totally new questions, an activity that caught attention and gave reputation to the pump.[22] He described the evacuated space inside the pump-receiver as a 'vacuum', but to distinguish this space from the philosophical term he defined it as a space 'not wherein no body at all, but such as is either, or almost totally devoid of Air'.[23] Correspondingly, 'Vacuum Boyliano' was not a perfect vacuum, but was 'such a vacuity or Absence of Common Air as is wont to be effected or produc'd in the operations of the Machina Boyliana' (Boyle's air-pump).[24] He objected the old idea of 'Nature abhors a vacuum' but declined to take a stand on whether a perfect vacuum was possible or not.[25] I thus see Boyle's efforts as a step in the process of giving the concept of a 'vacuum' a new meaning, one outside the old philosophical usage of the term.

### 1.2 Pump characteristics

There have been several modern endeavours to describe and define the air-pump and its applications in the seventeenth and early eighteenth century. Typical they focus on it as a philosophical instrument, used for investigations and demonstrations of various phenomena.

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[21] Helden (1991), 151.
[22] Ibid, 154.
[23] *Boyle's Works*, i, 163.
[24] Ibid, vi, 216.
[25] Ibid, x, 534.

The air-pump of the eighteenth century has been seen mainly as a device for showing phenomena revealed by Guericke, Boyle, Hooke, etc. in the previous century. However, the present study brings to light that the uses of the pump were much more complex and multifaceted in this period than considered by most authors. It was applied in research as well as in demonstrations and was found useful for practical purposes. To us the early air-pumps would fit into the concept of a 'scientific instrument'. This is a modern phrase, however, not used until long after the actual period. The air-pump is traditionally described as a 'Philosophical instrument', a term coined in 1681 by Nehemiah Grew (1628-1712), and still used by many instrument-historians.[32] According to a few short-form descriptions of early air-pumps, modern authors have been concerned about two characteristics of it. First, they put emphasis the artificial environment that is created inside the receiver, where extreme conditions exist for isolating, manipulating, and controlling various phenomena. Second, the phenomena that took place inside the receiver were of a novel kind that could not be produced or seen by other means. See Table 1.

| |
|---|
| 'The air-pump provided the experimenters with a convenient artificial environment in which to experiment'. (Helden).[26] |
| 'The air-pump (and the particle accelerator) create extreme conditions that do not occur natural on the earth'. (Helden and Hankins).[27] |
| The air-pump (...) distorted nature by producing an unnatural condition; (...) it 'tortured' nature to reveal its secrets. (Hankins and Silverman).[28] |
| 'The air-pump made it possible to isolate phenomena in a controlled laboratory environment'. (Hackmann).[29] |
| 'The air-pump, (and the electric generator), manipulated the natural world in an unprecedented way'. (Bennett).[30] |
| 'The air-pump (and the telescope, microscope, etc.) were exploratory devices for revealing things that could not otherwise be seen'. (Turner).[31] |

**Table 1.** Air-pump characteristics. The examples are taken from texts dealing with the history of scientific instruments.

These examples grasp several essential issues about the device as a philosophical (or scientific) instrument for investigation and demonstration, and so allude to the complicated nature of the instrument itself, or to be more specific, the complicated nature of the *implications* of this device. For example, today we take it more or less

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[26] A. van Helden, 'The birth of the modern Scientific instrument, 1550-1700', in J. Burke (ed.), *The uses of Science in the Age of Newton,* (Los Angeles, 1983), 62.

[27] A. van Helden and T. L. Hankins, 'Introduction: Instruments in the History of Science', *Osiris,* 9 (1994), 4.

[28] T. Hankins and R. Silverman, *Instruments and the Imagination* (Princeton, 1999).

[29] W. Hackmann, 'Scientific instruments: Models of brass and aid to discovery', in Gooding (1989), 40.

[30] J. Bennett, 'A Viol of Water or a Wedge of Glass', in Gooding (1989), 108.

[31] A. Turner, *Early scientific instruments, Europe, 1400-1800* (London, 1987), 153.

[32] Grew, N, *Musæum Regalis Societatis. Or a Catalogue & Description of the Natural and Artificial Rarities Belonging to the Royal Society and Preserved At Gresham College* (London, 1681), 357-70.

for granted that experiments using air-pumps (vacuum-pumps) can give new knowledge about Nature, but this was not the only opinion in the actual period. The contemporary debate whether unprecedented results from air-pump experiments could be used to make relevant knowledge claims, that is, if they could produce new facts about Nature, is discussed in depth by Shapin and Schaffer in *Leviathan and the air-pump*. This is a review of Boyle's pumps and experiments from political, sociological, and philosophical points of view. However, aspects of construction are not dealt with much. Another author, J. Golinski, portrays laboratory work as the creation of an 'artificial reality', a concept that fits well with the characteristics of the air-pump provided above. This 'artificial reality' is an arrangement of the natural world that is real, but different from Nature as it exists independently of human influence.[33] It is this concept of the early air-pump, as a machine that could create a reality that was artificial and different from the surrounding natural environment, that has been most frequently discussed by modern authors. The problem was how new and valid knowledge about Nature could be produced from this 'un-natural', artificial and man-made environment.

However, the importance of the air-pump is much more far-reaching than expressed by Shapin and Schaffer, Golinski and the authors cited in Table 1. The air-pump is consistently referred to as one of the most important scientific instruments to be invented in the seventeenth century, ranking with the telescope, the microscope, the thermometer, the barometer and the pendulum clock.[34] But while exemplars of these instruments can still be found in museums and collections, few contemporary air-pumps have survived. The modern literature about instruments from this period shows a similar pattern: much is written about the first ones, but the corresponding writings on air-pumps themselves are scarce. It does not require any especially meticulous investigations of the relevant sources to see that the air-pump of the early eighteenth century is 'under-studied'. A reading of texts from 1700 and onwards makes it clear that the functions and applications of the pump were much wider and more complex than discussed by Shapin and Schaffer. At this stage, the debate about the existence of a void and about the air-pump as a producer of new knowledge had more or less come to an end, but the period saw many new settings for the engine. I believe that the modern concepts of the early air-pump as a complicated philosophical instrument with great social and philosophical implications, especially for the 'scientific method', are very much due to the influential role of Shapin and Schaffer's book. Despite the fact that they terminated their studies on Boyle, Hobbes and the air-pump around 1675,[35] other modern authors have not always distinguished between the various uses and functions of the air-pumps of the seventeenth century, and those of the early

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[33] J. Golinski, *Making Natural Knowledge* (Cambridge, 1998). 331.
[34] W. Middleton, *The History of the Barometer* (Baltimore, 1964).
[35] Shapin and Schaffer (1985), 7, 276.

eighteenth century.[36] The descriptions quoted in Table 1 make no distinction: it is in fact the major role of seventeenth-century pump that is described.[37] If these pumps can be considered as the first generation of English air-pumps, I consider those by Hauksbee and his followers in the first half of the eighteenth century to belong to the second generation. The fact that these pumps had advantages over Boyle's is of course known, but there exists no methodical attempts to describe their technical development, or differentiate between the various uses of them as philosophical and practical instruments. However, a comprehensive study of Hauksbee's air-pumps and air-pump practice is precisely what I will do in this thesis, and use my findings to understand the transition from Boyle to Wright, and beyond.

### 1.3 Present work

A literature survey on the actual problems includes studies of texts on air-pump history, as well as on the key figure, Francis Hauksbee. Some extensive studies of Hauksbee were carried out in the 1950s and 1960s by Henry Guerlac and Duane Roller.[38] Roller focused on Hauksbee's theories of electricity, while Guerlac did the most comprehensive study of Hauksbee's life undertaken so far. Their studies have been important for shaping the modern image of Hauksbee but are not sufficient to explain the transition in pneumatics described above. In the later years, a few studies on Hauksbee and his influence on natural philosophy in the early eighteenth century have been undertaken. Most of these are discussing his work on electricity, his relation to Isaac Newton and a possible influence on Newton's theories of light, as well as his role in the Royal Society and in public lecturing.[39] None of these studies goes into depth on the air-pump. The latest contribution on Hauksbee, the entry on him in the new *Oxford Dictionary of National Biography* (2004), does not mention the double-barrelled air-pump at all.[40]

Generally speaking, there are not many studies of the history of the English air-pump. In addition to *Leviathan and the air-pump,* there exist a few general articles

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[36] A. C. van Helden, 'Air-pump and Vacuum-pump', in J. Heilbron (ed.) *The Oxford Companion to the History of Modern Science* (Oxford, 2003), 18.

[37] The texts where the examples in Table 1 are found do not distinguish between seventeenth and eighteenth-century air-pumps.

[38] D. Roller and D. H. D. Roller, 'Francis Hauksbee', *Scientific American,* vol. 189, no. 2 (1953), 65-69;
D. Roller and D. H. D. Roller, 'The Development of the Concept of Electric Charge. Part 3. 'Francis Hauksbee's experiments', in J. Conant (ed.), *Harvard Case Histories in Experimental Science* (Cambridge, Mass. 1957);
H. Guerlac, 'Sir Isaac and the Ingenious Mr. Hauksbee', in B. Cohen and R. Taton (eds.), *Melanges Alexander Koyre: L'aventure De La Science* (Paris, 1964), 229-53.

[39] G. Freudenthal, 'Electricity Between Chemistry and Physics: The Simultaneous Itineraries of Francis Hauksbee, Samuel Wall, and Pierre Polinière', *Historical Studies in the Physical Sciences,* Vol. 11(1981), 203-29;
S. Pumfrey, 'Who did the work? Experimental Philosophers and public demonstrators in Augustan England', *BJHS* 28 (1995), 131-56.

[40] S. Pumfrey, 'Hauksbee, Francis' in H. Matthew, et al. (eds.) *Oxford Dictionary of National Biographies* (Oxford, 2004) [*ODNB*].

about the history of the air-pump in English, for example by Anne C. van Helden, but no one goes into detail regarding Hauksbee's pumps or background.[41] A detailed study of Huygens's air-pumps has been undertaken by Alice Stroup, but a similar one on Hauksbee has never been attempted.[42] Other authors who have discussed Hauksbee, like Westfall, Hackmann, and Heilbron, have added little to Guerlac's findings on these issues.[43] Alto Brachner's book, *Geschichte der Vakuumpumpen*, was the only comprehensive text that I could find on the topic. It gives a general account of the pump from the seventeenth to the twentieth century, but does not explore English scientific circles deeply.[44] According to Heilbron, there are, for example, no texts that describe and discuss the air-pump to the same extent as Hackmann has undertaken with the electrical machine of the eighteenth century in his book, *Electricity From Glass*.[45]

It is a common impression that the air-pump of the first half of the eighteenth century was primarily used in education and entertainment by demonstrating known phenomena.[46] In spite this modern assumption, a search in the literature reveals few comprehensive studies on this topic. Little seems to have been written about *how* the air-pump was used, *what* it showed, and about what *context* it was used in. Of course, it is well known that air-pump experiments played an important part in the public lectures that were arranged in London during the period. The social importance of these lectures and their contribution to public understanding of natural philosophy are well described by Larry Stewart.[47] However, his study does not go into the details of the lectures themselves, no experiment or instrument is for example discussed in particular. Another good review of these lectures is found in Morton and Wess's work on the George III collection.[48] In opposition to Stewart, the emphasis in their account is on the instruments and instrument-makers. It holds much information about the growth and content of these lectures; the air-pump, however, is only one among many other instruments in this context. In the end I realised that a comprehensive study of English air-pumps and air-pump practice in the first half of the eighteenth century has never been undertaken. Unwinding this history is the intention of my thesis.

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[41] Helden (1991); A. C. van Helden, 'Theory and Practice in Air-Pump Construction', *Annals of Science*, 51 (1994), 477-495.

[42] A. Stroup, 'Christiaan Huygens & the Development of the Air-pumps', *Janus*, LXVIII (1981), 129-58.

[43] See for example: R. Westfall, *Never at rest. A biography of Isaac Newton* (Cambridge, 1998); W. Hackmann, *Electricity from Glass* (Alphen aan den Rijn; The Netherlands, 1978); J. Heilbron, Electricity in the 17th and 18th centuries: A study of early modern physics (Berkeley, 1979).

[44] A. Brachner, *Geschichte der Vakuumpumpen* (Deutches Museum, München, Undated).

[45] J. Heilbron, 'Some uses for catalogues of old scientific instruments', in R. G. W. Anderson (ed.), *Making Instruments Count*, (Cambridge, 1993), 13. According to Heilbron, a such study would be a particularly rewarding subject.

[46] A. C. van Helden, 'Air-pumps' in R. Bud and D. Warner (eds.), *Instruments of Science, an Historical Encyclopedia* (London, 1998), 19.

[47] L. Stewart, *The rise of Public Science* (Cambridge, 1992).

[48] A. Morton and J. Wess, *Public & private science* (Oxford, 1993).

## 2. The classic image of Hauksbee

Francis Hauksbee is a fascinating character who has been variously described as an instrument-maker, physicist, scientist, inventor, experimenter, natural philosopher, public lecturer, author, curator, as well as a student of Robert Boyle. Modern studies have often emphasised his attempts to explain electric phenomena, his role as a demonstrator in the Royal Society and in public lectures, and his doubled-barrelled air-pump. His background has been described as a 'mystery'.[49] Until now, it has been held that his first known public appearance was at a Royal Society meeting on 15 December 1703, where he presented and performed some experiments with an air-pump. The lack of information on his previous activities, especially on where he had learned to make his highly efficient double-barrelled pump, has led to numerous speculations. I shall seek to dispel this 'mystery', and will use my findings to explain how Hauksbee and his followers developed the air-pump and its applications; and further how this led to establish pneumatics as a distinct subject.

The classic image of Hauksbee is a complex one. Some key elements are beliefs about his background, the origin of his double-barrelled pump, and his early performances in the Royal Society. He is well-known by his book, *Physico-Mechanical Experiments* of 1709 (reprint 1719),[50] his articles in the *Philosophical Transactions,* his demonstrations in the Royal Society, and by his public lecturing on natural philosophy. However, these sources give the impression of a man well-versed in natural philosophy, and with outstanding skills in instrument making, experimenting, lecturing and writing. So who was he? Where did he come from? Where had he achieved all these skills? What brought him to the Royal Society in the first place? These questions arise naturally, since very little has been known about him before he suddenly appeared in the Royal Society. The starting point for answering these questions has normally been the entry in the 'Journal Book' of the Royal Society that day, saying that 'Mr. Hawksbee shewed a New Invented Air-Pump and in it, upon the Mercury descending a Light Etc. He was thanked'.[51] His first appearance in fact took place at the meeting where Isaac Newton was in charge for the first time – as the newly elected president – and has been seen in connection with Newton's initiative to restore the Society. But where did Newton learn about him?

A careful study of the double-barrelled air-pump, both by reading Hauksbee's own account as well as examining the few surviving examples of it, clearly underlines the mystery. This pump is a masterpiece, a well-working, easy-to-operate machine, with thoroughly prepared functions and furnished with beautiful

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[49] J. Heilbron, *Electricity in the 17th and 18th centuries: A study of early Modern physics* (Berkeley, 1979), 229.
[50] F. Hauksbee, *Physico-Mechanical Experiments* (London, 1709, reprint 1719).
[51] The Royal Society, 'The Journal Book, JBC 10 (London, 1702-1714), 15 Dec. 1703.

ornaments. See Figure 5. Also a few contemporary notes acclaim Hauksbee's air-pump as 'improved',[52] and 'the best they ever had seen'.[53] So where had he learned to make them? Also the experiment that he is believed to have made during his very first performance is rather advanced, which has raised questions on where he gained his necessary knowledge in experimental philosophy. From this point of view, Hauksbee's background *is* a mystery.

Historians of science have expressed this issue in various ways, for example like Henry Guerlac, who wrote that Hauksbee 'emerged from obscurity'.[54] According to John Heilbron, 'it is unknown how Hauksbee had prepared himself as an experimenter and how he came to Newton's attention'.[55] Richard Westfall asserted that 'we know nothing of Hauksbee's origin and background'[56] and that no one today seems able to define precisely what his improvements of the air-pump were.[57] The entry on Hauksbee in the *Oxford Dictionary of National Biography* does not yield much new light on these aspects of Hauksbee either.

The confusion and uncertainty over Hauksbee's background and origin of his air-pump is not a new one. In 1849, George Wilson wrote that the 'history of the English air-pump is in great confusion'.[58] He used a lot of space to argue that the double-barrelled air-pump in possession of the Royal Society could not have belonged to Boyle, something that was commonly assumed at that time. It was possibly a relic of Hooke, but most likely made by Hauksbee. This pump, still on display in the Royal Society in London is undeniably a Hauksbee pump. Wilson explained much of the confusion by impreciseness in series of writings from the second half of the eighteenth century and onwards. The error seems to be even older, however. In the 1736 edition of John Harris's *Lexicon Technicum,* Hauksbee's own description of his double-barrelled air-pump is inserted into the text on Boyle's pumps, and in such a way that it gives the impression of this pump being ordered by Boyle and manufactured by 'Mr G. and Dr. Hook'. Hauksbee himself is not mentioned or given any credit at all.

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[52] *The Daily Courant*, 9 Dec. 1704.
[53] J. Harris, *Lexicon Technicum* (London, 1704), under 'Air-pumps'.
[54] H. Guerlac, 'F. Hauksbee', in C. C. Gillispie (ed.), *Dictionary of scientific biography* (16 vols, New York, 1981), iv, 169.
[55] J. Heilbron, *Electricity in the 17th and 18th centuries: A study of early Modern physics.* (Berkeley, 1979), 229.
[56] R. Westfall (1998), 632.
[57] R. Westfall, (ed.), *The Galileo Project*, http://galileo.rice.edu/Catalog/NewFiles/hauksbee.html.
[58] G. Wilson, 'On the Early History of the Air-pumps in England', *The Edinburgh New Philosophical Journal*, XLVI (1849), 330–54.

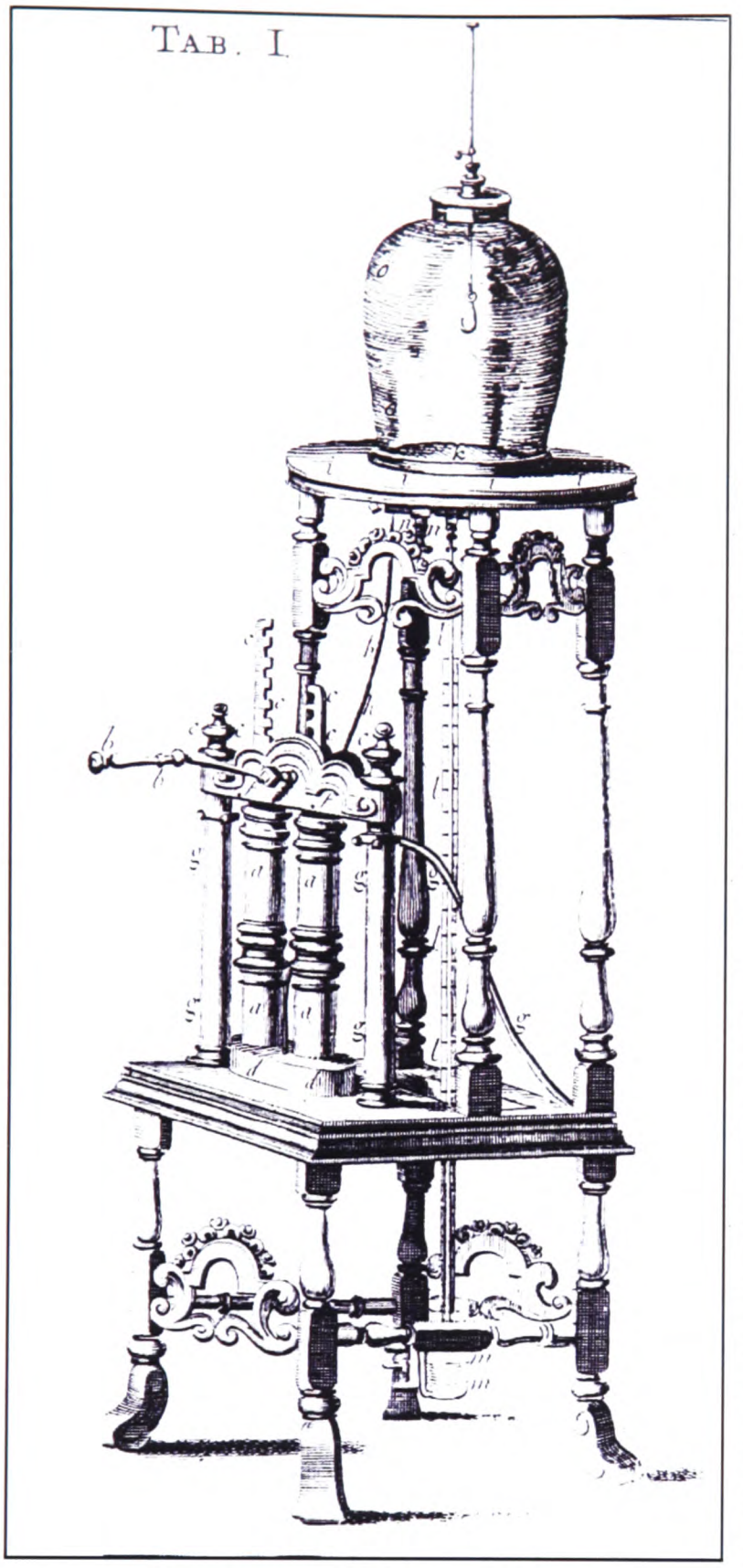



**Figure 5.** Hauksbee's double-barrelled air-pump. *PME* (1719)

Another element in the early confusion is the fact that Hauksbee had a nephew with the same name. Francis Hauksbee Junior was also an instrument-maker and a public lecturer, as well as engaged with the Royal Society. They were often mistaken for the same person during the nineteenth century, for example by John Nichols[59], and even as late as the mid-twentieth century their diverse merits were mixed up by the influential instrument-historian Maurice Daumas.[60]

Guerlac was especially concerned about the lack of information on Hauksbee's background. In the discussion found in 'Sir Isaac and the ingenious Mr. Hauksbee' from 1964,[61] he proposed that Hauksbee might have been one of Robert Boyle's domestics, in an attempt to explain Hauksbee's ability to build air-pumps and familiarity with experimental philosophy. It is well-known that Boyle used many servants and helpers to perform the experiments, and the idea that Hauksbee could have been one of these makes sense to some extent.[62] Others see Robert Hooke or Denis Papin as more likely candidates as Hauksbee's former master, but no one has been able to come up with any textual evidence. The idea of explaining Hauksbee's background by describing him as one of Boyle's domestics is repeated over and over again, and seems to have become established as an accepted 'truth', especially in popular science books and

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[59] J. Nichols, *Illustrations of the Literary History of the eighteenth century* (8 vols, London, 1817), i, 56, 506 and iv, 810.

[60] M. Daumas, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers* (London, 1989), 234.

[61] H. Guerlac (1964), 228.

[62] S. Shapin, *A Social History of Truth* (Chicago, 1994), 355.

on the Internet. Some professional texts are more careful, for example *Leviathan and the air-pump,* where the authors write that Boyle's experiences might have been 'transmitted to Hauksbee'.[63]

The assumption of Hauksbee's as an associate of Boyle is also based on the belief that it was a double-barrelled air-pump that he presented at his first performance to the Royal Society on 15 December 1703. This supposition comes naturally since he never mentioned any other air-pumps in his publications. This contrivance has been explained by a connection to Boyle and Papin.[64] Many modern authors have simply seen Hauksbee's pump as an improved version of Papin's double-barrelled pump because of the similarities. The fact that Hauksbee repeated many of Boyle's experiments during his early demonstrations in the Royal Society has also been used to support the idea of a connection.[65]

Another issue that sometimes surfaces is the assumption that he performed some experiments with barometric light and electricity during his first performance. This seems to be based on the combination of the note in the 'Journal Book' and the accounts on his early electrical experiments. The idea has in turn been used to explain the first contact between Hauksbee and the Royal Society, for example like 'Francis Hauksbee's sr introduced himself to the Royal Society with demonstrations of glowing mercury'.[66]

### 2.1 Why I question the 'normal' account of Hauksbee

The idea of Hauksbee as one of Boyle's nameless domestics and his double-barrelled air-pump as a follow-up of Papin's is a convenient one. It explains how he got acquainted with air-pumps and natural philosophy; and also the similarities between the pumps – both had two interconnected barrels and self-closing valves. The differences between Papin's coarse and inconvenient model, and Hauksbee's elegant masterpiece are easily perceived as practical and esthetical differences only.

However, by approaching the primary sources from a technical point of view, I soon became uncertain about the soundness of the standard account. It became more and more difficult to get the image I achieved to fit into the commonly accepted ideas of Hauksbee and his pump. Through my literary survey, I realised that Hauksbee's pump had its origin in cupping and anatomical instrument making; with no direct reference to Papin's. There seemed also to have been another air-pump in the story, so far unknown to modern historians. The examinations of a few extant Hauksbee-pumps, using my technical background, suggested further that there were technologies involved not found with Papin. To me, the leaps from Boyle to Hauksbee's practice, and from Papin's to Hauksbee's pump seemed huge and discontinuous. A direct connection between Hauksbee and the world of Boyle,

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[63] Shapin and Schaffer (1985), 276.
[64] Guerlac (1964), 241.
[65] Ibid, 240.
[66] L. Roberts, 'Science becomes electric', *Isis* Vol. 90, No 4, (Dec. 1999), 684.

Papin and indeed Hooke could not be ruled out, but I found it insufficient to explain the qualities of the pump and Hauksbee's use of it.

Some important events must have taken place in Hauksbee's career that made him able to make such a beautiful and complicated instrument, and to perform his variety of experiments. Searching for it is my objective here.

## 3. Outline

The thesis is organised in two parts. In Part 1, *Making the air-pump* (Chapter 1-3), I discuss the development of Hauksbee's air-pumps and air-pump accessories, and show how this created the technological basis for establishing pneumatics as an appreciated and useful subject. This material will be applied in Part 2, *Using the air-pump* (Chapter 4-6), where I discuss various applications of the pump and use them to explain how the transition from Boyle to Wright, and as well as further progress, became possible. There is a short summary after each chapter, recounting the most important findings and arguments.

The traditional source-material on Hauksbee has been his book and articles, the 'Journal Book' of the Royal Society, as well as some advertisements and course syllabuses on public lectures. It is however apparent that there are several documents on Hauksbee in the Royal Society that are not fully appreciated by historians. I also discovered that the first edition of Harris's *Lexicon Technicum* from 1704 differs considerably from the 1737 issue, as it contains valuable information on Hauksbee's first air-pump. Another important finding was a series of sales-advertisement by him from before 1703, which clearly sheds light on his early activities. There is also unexploited material on Hauksbee in books and articles from his own period, as well as relevant texts on air-pump applications from for example William Derham (1657-1735), Stephen Hales (1677-1761) and Alexander Monro (1697-1767). I will draw on all these, as well as the secondary literature mentioned above.

I have also replicated one of Hauksbee's instruments, the rotating globe machine from 1706, and will use my experience from demonstrations with it as a complementary source, together with the textual ones.

In **Chapter 1** I argue that Hauksbee's competence as an exceptional air-pump maker was developed between 1699 and 1703, as a result of his experiences with construction and manufacturing of cupping glasses. Cupping and blood-letting was a much-used remedy for a series of illnesses at the time, and Hauksbee's cupping utensils contained a new design, where syringes were used to evacuate the glasses, instead of the traditional way by fire or mouth suction. I demonstrate that these syringes, which in fact were small air-pumps, became perfected between 1699 and 1701 in attempts to satisfy the customers.

I further show how a larger syringe, introduced in 1701, served as a transition from the cupping syringe to his first air-pump for use in natural philosophy. This syringe was described as a 'combined engine', which could serve as both an air-pump; a condensing engine for compressing air; and as a syringe for injecting air, wax, or mercury into pathological specimens.

Hauksbee's engagement in anatomy has until now been unknown. I describe his injecting instruments and argue that there was one important connection between these instruments, the cupping utensils and the air-pump. This was a valve: a reliable, uni-directional, self-closing contrivance originally developed for use with cupping utensils. The device became crucial for Hauksbee's most important instruments in medicine and natural philosophy,

**Chapter 2** is a survey of Hauksbee's first air-pump. Such a review is vital for understanding Hauksbee's air-pumps generally, and how his early model provided a background for further development, practice, and various applications of air-pumps and pneumatics.

The earliest evidence I have found of an air-pump with two barrels by Hauksbee is from May 1705. I therefore argue that the pump he demonstrated at the Royal Society in December 1703 was *not* the classic, double-barrelled one, as has normally been assumed, but another, until now unidentified, type. I argue that this was the single-barrelled model, introduced in 1701 as a further development of the combined engine. I then assess several contemporary appraisals of Hauksbee's 'improved' air-pump and show that they were all directed towards this smaller version, and not to the classic one, as assumed by all modern commentators. Westfall has stated that 'no one has been able to specify what Hauksbee's improvements of the air-pump in fact consisted in'. I answer this question here by comparing Hauksbee's single-barrelled pump with earlier air-pumps by Boyle, Hooke and Papin, and using Hauksbee's own concepts like 'ease' and 'exactness'. I demonstrate that these terms alluded to easy and convenient leak-tightening and handling of the receiver, exact pressure-measurements by an in-built barometer; and to an air-inlet function of this pump. Further, I show that, at this stage, Hauksbee had developed a series of air-pump accessories for use in experimental philosophy.

Based on this evidence, I finally argue that these issues contributed to facilitate convenient and reproducible experiments, and thus constituted a preliminary background for the circumstances depicted by Joseph Wright.

The well-known, classic, double-barrelled air-pump is often thought of as Hauksbee's most important instrument. In **Chapter 3** I raise serious doubts about this perception. I examine the technical dissimilarities between the two models, and although the classic one was a beautiful, well functioning masterpiece that might have had social consequences for Hauksbee personally, I show that the difference it could make on scientific practice could not have been very large. I further argue that the leap from Boyle's and Papin's pumps to Hauksbee's smaller, single-barrelled model was much greater and more important than the step from his single to his double-barrelled one.

The new pump was announced in the newspapers, but I have found no direct evidence of this change of technology elsewhere in the written material. It is also evident that Hauksbee seldom mentioned the air-pump explicitly in the experimental records. I use the lack of information here as a starting point to discuss technical, scientific and social aspects of the air-pumps. The concept of black-boxing is important here, and I claim that Hauksbee, even in his single-barrelled model, managed to perfect the air-pump to a level where it no longer needed much attention or explanation in texts. It was thus ready for settings like Wright's, where the effects were the essential and the operation a routine.

Finally, I argue that the air-pump reached its 'stabilized form' with Hauksbee's double-barrelled model, a pump-concept that lasted to the twentieth century.

**Chapter 4** is about the different stages of development and use of the air-pump by Hauksbee and other practitioners. I first show how attention moved away from the pump itself and towards external instrumentation. It becomes clear that the air-pump developed from a state where the pump-cylinder and the receiver were integrated in one unit through pumps with separate barrels and receivers, to pumps using a series of specialized receivers. Further, I discuss how experiments and demonstrations were performed at this stage, giving examples on animal-tests, glass-breaking, and the firing of gunpowder in the vacuum inside such purpose-made receivers. Here I show that these experiments contributed to popularise the vacuum-concept through visualization and illustrated concepts involving phenomena regarding pressure, spring and weight of air.

I also show that the air-pump developed further, to a stage where pump-accessories came to be regarded as more significant than the pump itself. I exemplify this by discussing a few of Hauksbee's instruments, the rotating globes and cylinders, and a hollow prism, all of which could be evacuated by the pump. From this I claim that the air-pump here had became downgraded to a supplier of vacuum only, with no other purposes in the experiments.

Finally, I argue that the various applications of Hauksbee's air-pump and air-pump accessories brought pneumatics to a state where the pump became regarded as a black-boxed and unproblematic tool; and where *vacuum* became thought of and handled as an object.

In **Chapter 5** I discuss how the application-area of the air-pump expanded during the first half of the eighteenth century, from being an important philosophical instrument available to only a small group, to a publicly accessible device for use in public and private demonstrations. According to Stewart, the experiments that were shown at public lectures in London during this period served as practical counterparts to the queries in Newton's *Opticks*, and were together crucial for disseminating natural philosophy and Newtonianism. I discuss the role of pneumatics in this undertaking, and show that, for example, basic properties like pressure, spring and omni-directionality of atmospheric air were made familiar to the public through cupping-related experiments. I also show that a private market for air-pumps, air-pump accessories and technical literature had developed by 1720, claiming that one reason was the improved quality of the instruments. The equipment had become handy and reliable, as well as easily available, which facilitated settings like Wright's. Further I argue that all these activities contributed to transform pneumatics into an established field within natural philosophy, to a subject with its own accepted methods, terminology, literature, instruments and craftsmen.

Hauksbee had apprentices and other associates who were engaged in the production of pneumatic instruments. I discuss how this activity, conducted by a few practitioners, evolved into a profession. Further I show that Hauksbee and his followers formed a small group of instrument-makers that was active in London up until about 1745, and operated separately and independently of the optical, mathematical and philosophical instrument-makers. In addition to manufacturing air-pumps and other pneumatical instruments as well as medical utensils, most of them were also engaged in public lecturing on natural philosophy. I denote this group as the 'Pneumaticians'.

The focus in **Chapter 6** is about research by air-pumps and goes beyond the Wright-image. The number of natural philosophers who performed novel investigations with the air-pump in this period is said to be very small. Francis Hauksbee's own work on static electricity has been mentioned as the only exception of such an activity. However, the air-pump *was* used for research in this period, in addition to the usual demonstrations. I show this by discussing Stephen Hales' use of the device for investigations on plants, animals, and the air – where it acted as a rather obscure research instrument. Further I discuss Alexander Monro's activities of preparing pathological specimens, and show how the air-pump became used as merely a manufacturing tool. The air-pump as a practical

tool is definitely *not* included in the modern characteristics of the seventeenth and eighteenth century air-pump. From this I argue that pneumatics had developed even further, to yet another stage, where it served as a supporting agency for other sciences.

The aim is to show that the air-pump had now (ca 1745) approached a level of versatility where it functioned as an unproblematic tool and method, where both the instruments and theories in pneumatics were regarded as fully accepted and 'black boxed' by practitioners working in other fields. Pneumatics was established and had become absorbed into larger realms, both theoretically, and practically.

The replication process of Hauksbee's rotating globe machine, including methodological considerations of such undertakings, is discussed in the **Appendix.**

Part 1

# Making the air-pump

# Chapter 1
# The unknown Hauksbee – from medicine to natural philosophy

## Introduction

This chapter is about Francis Hauksbee's engagement in pneumatics in the period before he arrived at the Royal Society in December 1703.

Since Guerlac undertook his studies in the 1950s, a bit more about Francis Hauksbee's background has been revealed. By the efforts of various historians, for example Westfall and Pumfrey, we now know that he was born in Colchester, Essex in 1660 (baptized on 27 May) and was the son of Richard Hauksbee (b. 1621), a draper and common councillor of the town. Francis was apprenticed as a draper to his elder brother John from 1678 to 1685, and belonged to the Draper's Company in London. He was married to Mary (who died after 1730) by 1687, and had five children. He lived in Queen's Head Court in Giltspur Street, London, but moved to Wine-Office Court in 1710, and to Hind Court in 1712, both off Fleet Street. He died in April 1713.[67]

The fact that Hauksbee seems to have been a professional draper has puzzled modern historians, who have described him as a 'draper turned instrument-maker'.[68] But Hauksbee's actual relationship to the draping profession is unclear. To trade in London a man had to be a 'Freeman', that is, belonging to a Guild – and these memberships were often inherited.[69] However, Hauksbee's published and

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[67] *ODNB,* under 'Hauksbee'.

[68] J. Heilbron, *Physics At the Royal Society During Newton's Presidency* (Los Angeles, 1983), 30.

[69] D. Mortorff, *The Drapers Company of London.* http://www.combs-families.org/combs/records/england/drapers-hist.htm Several mathematical instrument-makers were, for example, members of the Grocers Company. See: J. Brown, *Mathematical Instrument-Makers in the Grocers' Company 1688-1800* (London, 1979), iii.

unpublished writings reveal no evidence about his alleged association to this type of trade. Furthermore, the records of the Royal Society, other contemporary sources on natural philosophy, and the records of the Drapers Company give no hints about this relationship.[70]

The question of how Hauksbee became involved in the business of scientific instrument-making is still unclear. Perhaps it was through his elder brother John to whom he was apprenticed: John – who also was Francis Hauksbee Junior's father – might have been involved in the trade, so that the elder and the younger Francis could have inherited the engagement from him. However, after periods of research I had to leave this and similar enquiries about Hauksbee's background without any proper conclusion. What I nevertheless became able to solve is the more important riddle about the origin and development of Hauksbee's well-known double-barrelled air-pump. And the facts that came up were rather surprising.

In 1704, John Harris portrayed Hauksbee in *Lexicon Technicum* as an 'Ingenious and Industrious Artificer', who made mathematical and philosophical instruments, including air-pumps. This pump, with all its crucial components, was described in detail. Hauksbee was also referred to under the entry *Cucurbitula*, which means cupping glasses. On a plate with illustrations of pneumatic apparatus, Harris gave a picture of a small cupping device made by Hauksbee, as well as one of his air-pump.[71] See Figure 6. In this chapter I explain the relationship between these two items, and argue that Hauksbee's air-pumps had their roots in cupping practice.

Robert Boyle had previously pointed out that the conditions in traditional cupping glasses resembled those that took place in an air-pump-receiver. From a series of cumbersome experiments, triggered by discussions with the Jesuit Franciscus Linus (1595-1675) about suspension of mercury in barometers as well as the swelling of human skin in cupping glasses, Boyle concluded that cupping by air-pumps was more efficient than by heat.[72] He also performed series of experiments with syringes, but there is no indication that Boyle thought of combining syringes and cupping-glasses for practical and commercial applications.[73] [74]

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[70] Details on him, his father, his wife, his brother and his nephew are found in 'Boyd's Roll on the Drapers Company, but without any references to an engagement in natural philosophy. Boyd's Roll, A/11/06/1664, 1583; A/04/12/1678, 1584; P/02/08/1714, 1585; A/12/10/1720, 1583.

[71] Harris (1704), plate with air-pumps.

[72] The fact that the controversy with Linus (whether suspension of the mercury was caused by the weight of the atmosphere or some invisible cords or funiculars) resulted in the formulation of 'Boyle's Law' is well known. However, that Linus used similar arguments to explain the effects in cupping glasses has never been commented on. See *Boyle's Works*, iii, 3, 78, 100.

[73] For a discussion on the background of Boyle's Law, see: Shapin and Schaffer (1985), and Middleton (1964).

[74] All other examined seventeenth-century sources on cupping prescribed heat or mouth-suction, or did not mention any particular method at all. See: J. Woodall, *The Surgeons Mate* (London, 1639); A. Paré, *An Explanation of the Fashion and Use of Three and Fifty Instruments of Chirurgery* (Edinburgh, 1634); N. Culpeper, *Two Treatises, The First of Blood-Letting, and The Second of Cupping and Scarifying* (London, 1672).

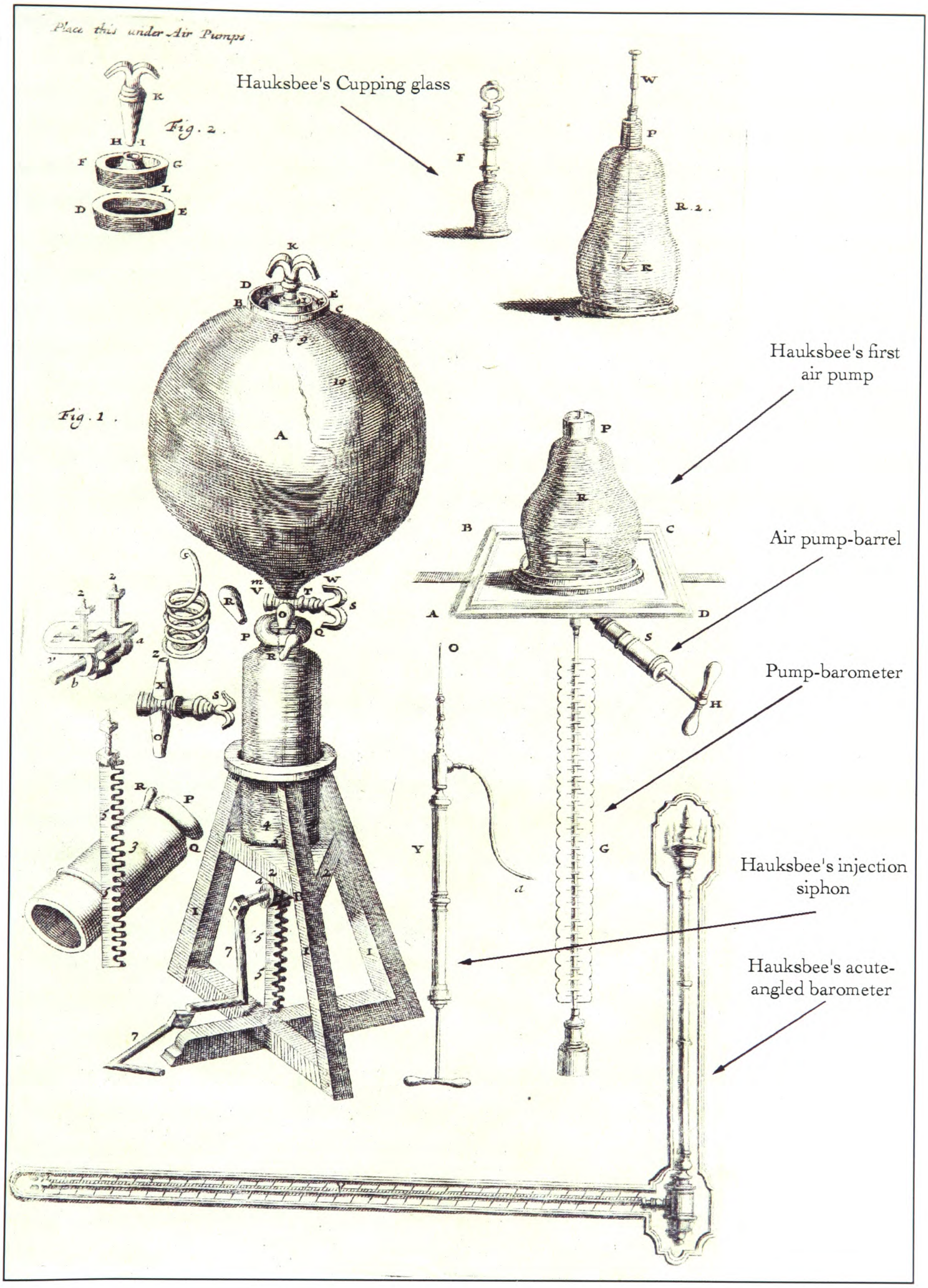



**Figure 6.** Pneumatic instruments. From J. Harris, *Lexicon Technicum* (London, 1704).

30 years later, however, Hauksbee turned this relationship into commercial objects. It is not unlikely that Hauksbee was aware of Boyle's work on this, but I have not been able to find any direct links.

I show how the development from cupping to air-pumps took place technically, evolving from Hauksbee's cupping utensils to a multi-purpose engine launched in 1701, a device that could serve as an air-pump, a condensing engine and an anatomical injector. The crucial component in these instruments was a valve, which Hauksbee originally developed and refined for use in commercial cupping devices in attempts to increase customer satisfaction. Hauksbee's first separate air-pump was introduced in October 1702, and I show that this instrument, as well as separate condensers and injectors, were built on experiences achieved from the cupping utensils and the combined engine.

Most of this reconstruction is based on Hauksbee's early sales advertisements (never before consulted by historians) and Harris's *Lexicon Technicum* (1704), where I use my experiences with making and using modern scientific instruments, as well as with restoring and replicate old ones, to fill the gaps in evidence.

## 1.1 A new way of cupping

I shall in this section describe various aspects of Hauksbee's cupping utensils. A detailed discussion of both construction-features and construction-methods elaborate the overall connection between these devices and the air-pump.

### 1.1.1 Theory and practice of cupping

The ancient methods of cupping and blood-letting were a common form of medical therapy in the early eighteenth century.[75] According to Galenic medicine, the mental and physical condition of a person was dependent on the balance between the four humours of the body: blood, phlegm, black bile and yellow bile.[76] These fluids correlated with the four elements: Earth, Water, Fire, and Air, representing dryness, wetness, heat and cold. It was generally believed that sickness could be caused by an imbalance of these fluids, and the remedy was to remove excessive amounts by blood-letting and cupping to restore the equilibrium. Harvey's discovery of the circulation of the blood in 1628 had in fact not diminished the popularity of these methods.[77] Francis Hauksbee became engaged in

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[75] Blakemore, C. and Jennett, S, *The Oxford Companion to the Body* (Oxford, 2001), 91.

[76] W. L. Jones, *Ministering to Minds Diseased, A history of Psychiatric Treatment,* (London, 1983), 7.

[77] The belief in blood letting and cupping as a remedy for most diseases was so strong that even healthy people choose to be bled each spring, as an 'annual cleaning'. See: Blakemore (2001), 91.

the trade of supplying equipment for this popular practice. The first evidence of such commercial activity by Hauksbee is an advertisement in *The Post Man* of 31 January 1699:

> A New way of Glass Cupping performed without Fire, Lamp, or Mouth Suction, Invented by F. Hauksbee, who liveth in Queens Head Court in Guilt Spurr Street, just without Newgate.[78]

Traditionally, there existed several ways to free the patient from these excessive and harmful humours. Leeches could be placed on the skin to suck out the 'ill' blood, veins could be opened by special knives for draining a required amount of blood, as well as by cupping.[79] In dry cupping, a heated glass cup would be placed over the assigned area, and as the air inside cooled, the cup would 'stick' to the skin by the reduced pressure that was obtained as the air contracted. This 'vacuum' sucked the blood to the skin and away from the internal parts where it was thought to congest. In wet cupping, the skin was punctured by a knife before the glass was applied, to allow removal of excessive blood.[80] The glasses were normally heated over a candle or by a torch or spirit lamp. Another method was to burn a piece of paper or tow inside the cup and heat its internal air, before the cup was applied to a patient.[81] Instead of using the heating and cooling of air to create a vacuum, similar effects could be achieved through mouth suction, where special cups, often made from horn, were used.[82]

Hauksbee described his particular method as different from these traditional ones, and declared it to be the most effective that had ever been put into practice. According to the advertisement, Hauksbee's method received the approval of all who saw it to be the best and was now being offered to 'gentlemen proper for its use, to the Benefit of the Publick'.[83] Hauksbee also invited physicians and surgeons to his house for demonstrations. Without giving any details, Hauksbee claimed that he himself had invented the method; one that was so simple that anyone who observed it was capable of repeating it. Hauksbee also advertised special glasses for cupping a whole finger or toe in once, something that had not been possible before, according to the newspaper announcements.

A few months later Hauksbee published another advertisement, now revealing more details.[84] He was selling several sorts of glasses, bigger and smaller, for a variety of uses, including the cupping of whole fingers or toes. Also scarifying fleams (a special knife for opening veins) and all other 'appurtenances' (accessories) that belong to the practice were available. But it becomes clear that

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[78] *The Post Man,* 31 Jan (1699).
[79] Blakemore (2001), 91.
[80] W. Brockbank, *Ancient Therapeutic Arts* (London, 1954), 67.
[81] Ibid, 81.
[82] Ibid, 70.
[83] *The Post Man* 31 Jan (1699).
[84] *The Flying Post,* 9 May (1699).

the crucial object was a small 'Engine', one that could be used with several glasses at a time. In examining these and later announcements, I found that this engine had to be a small syringe[85] that could be attached to the top of a cupping-glass, something that is visually confirmed by Harris (Figure 6). When a glass had been placed over the area to be cupped, the operator could evacuate its contained air by simply pulling the handle that was attached to the sucker. The glass could then be left in place after pumping, while the syringe was removed and applied to the next one. It was the action of an exhausting-syringe, instead of cooling and contracting air that created the suction.

### 1.1.2 Hauksbee's utensils

To be as easy to operate as Hauksbee claimed, these cupping utensils required several features not explicitly mentioned in the advertisements. One characteristic of cupping practice was that the glasses should be kept on the skin for a while, giving the 'sick' blood time to get out. For this to be possible with Hauksbee's glasses, they had to be left in place with a reduced pressure inside, once the pumping was finished. Hauksbee made it clear that a 'single engine' could be used with several glasses during a treatment, which implies, though never mentioned explicitly, that the glasses must have been equipped with a self-closing valve or a stopcock to close them off after pumping.[86] This was necessary for preventing air from rushing into the glasses when the syringe was removed. If a stopcock was used, it had to be fastened to the top of the glass, and opened and closed by manual turning of the vane. After a glass was sufficiently pumped and closed off, the syringe could be disconnected and used on the next glass.

But given Hauksbee's promises about the simplicity and 'self-explanatory' nature of his invention, the use of stopcocks also seems potentially questionably. Stopcocks required a complicated procedure of pulling and locking the plunger, and opening and closing the stopcock by turning the vane, all in the right order. It may be more likely, therefore, that the air-stopping mechanism on his early cupping glasses was a valve that was intended to shut automatically when the pressure inside the glass became lower than the outside one. Such a valve correspond well with both the advertised image of Hauksbee's utensils as simple devices, and also with the fact that the absence of stopcocks became an important issue later on with his syringes and air-pumps. The illustration of Hauksbee's cupping device that was given by Harris in 1704 showed no stopcock.

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[85] *The Post Man*, 2 Jan (1701).
[86] *The Flying Post*, 9 May (1699).

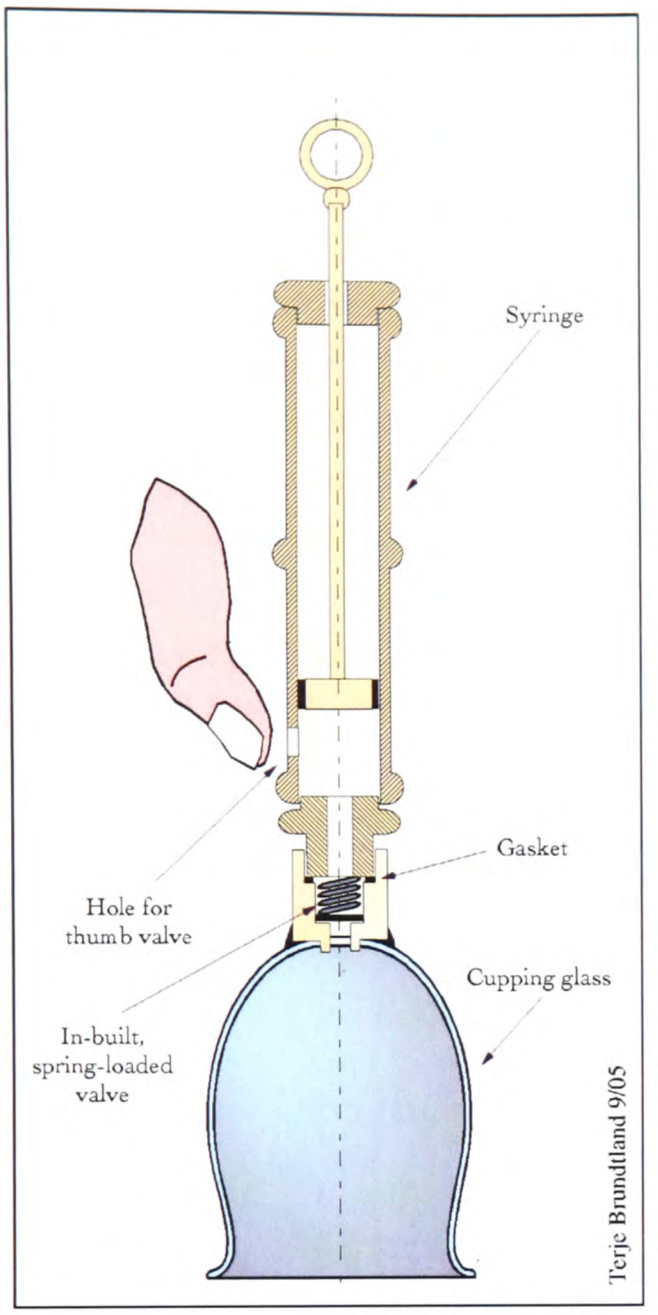



**Figure 7.** Francis Hauksbee's first cupping syringe, with a thumb-valve.

The concept of an automatically operated valve also correlates well the fact that his first syringes were supplied with a small hole on which 'the thumb was acting as a valve'.[87] Based on this information, a 'reconstruction' of Hauksbee's first cupping system is possible. The hole must have been located in the lower end of the syringe, penetrating the wall just above the position of the upper edge of the piston, when this was pushed to its most inwards position. The syringe was fastened to the brass cylinder on top of the glass, which contained the self-closing valve. See Figure 6, *F* and the reconstructed cross-section in Figure *7* The procedure for using these utensils would be much simpler than those with stopcocks. The operator simply had to place the cup on the patient's body while holding the syringe with his left hand, and the thumb covering the small hole. The plunger was then pulled outwards with the right hand, sucking the air out of the glass. With the piston at the outer end, or as far out as was needed to give the required suction, the thumb was then lifted, causing the outside air to rush into the syringe and force the self-closing valve on the glass to close automatically, thus preserving the vacuum. If another stroke was required, the sucker had to be pushed inwards to the start position and the thumb placed over the hole once more so that a new sequence could begin. The advantages of this system are obvious compared to one manipulating stopcocks. The operator just needed to pull the sucker outwards, lift his thumb a little, and a partial vacuum would be created in the glass.

Another question arises from studying this practice: if the same syringe could be used on several glasses during the treatment of a patient, it had to be connected and disconnected from the glasses rather easily. This aspect is important for several reasons. The task of mounting and dismounting a syringe from a cup had to be performed in a reasonably short time to avoid stress for the patient and the operator. This process also had to be performed without using too much force, so that the risk of the cups coming loose from the skin was minimised. Most importantly, the connection had to be leak-tight. To meet these conditions, as well

[87] *The Post Man*, 2 Jan (1701). This is one of the few technical details that were given in the advertisements.

as Hauksbee's promises about simplicity, the early syringe/glass connection was most likely a screw-on system, one made leak-tight with a leather gasket. This would make the connection/disconnection fast and reliable, providing the leather-seal was kept wet by a drop of water or oil occasionally.

### 1.1.3 Hauksbee's invention?

When reading Hauksbee's early advertisements, we could wish he had revealed more about the structure of this device. After making the reconstruction described above, I discovered that there exist two articles in the *Philosophical Transactions* by another actor that precisely do so. In June 1699, a man called Thomas Luffkin published a letter concerning some very old numerical figures on an escutcheon in a house in Colchester. The same letter also had a note about what he called a 'small air-pump' that could be applied to cupping glasses, made by his brothers. In October of the same year Luffkin gave a detailed account of these items.[88] I have not been able to find any particular links between Hauksbee and the Luffkins in the contemporary literature, but there are so many similarities that I argue for a connection between them, and a common origin to these devices. A review of Luffkin's cupping utensils may therefore explain Hauksbee's early instruments.

Hauksbee came from a family of drapers in Colchester.[89] The old figures described by Luffkin were found in a house in Colchester belonging to a linen draper. Hauksbee advertised in January and May, Luffkin wrote in June and October. It becomes clear in the first article that Luffkin already had a technical description about the items at hand, and that this was the one published in October. This means that in Colchester, Luffkin had built, tested and documented his instrument in the first half of 1699, which coincided with Hauksbee's activities in London. The most remarkable comparison is, however, that the instruments seem to be more or less identical. Both used a syringe with a solid piston to evacuate the cupping glasses. These devices also had in common a self-closing valve on top of the glasses, and both could mount and dismount the syringe to the glasses by screwing. See Figure 8. Even the function of using the thumb as a valve on the syringe was mutual.[90]

Hauksbee's material and advertisements in this period reveal little, probably because he was mindful of maintaining trade secrets. Luffkin, however, explained and published every detail of his device through text and illustrations, which helps us to understand Hauksbee. Whoever who came up with the idea of cupping by syringes – Luffkin's brothers or Hauksbee – Luffkin did not develop it any further and disappeared from the industry.[91] Hauksbee, however, turned them into

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[88] T. Luffkin, 'A letter', *PT*, vol. 21 (1699), 408-10. In Latin. An English translation is given in the abridged edition, *The Philosophical Transactions, Abridged and Disposed*, vol. iii (London,1749), 261-2.

[89] G. Clifton, *Directory of British Scientific Instrument-makers 1550-1851*, (1995), 128.

[90] T. Luffkin, 'An Extract of a Letter', *PT*, vol. 21 (1699), 287-8.

[91] If the term 'brother' also included 'brother in law' in this period, Luffkin's devices could in fact have been made by John or Francis Hauksbee.

functioning instruments that he advertised and sold. Hauksbee was also the one who got credit for the invention in *Lexicon Technicum*.

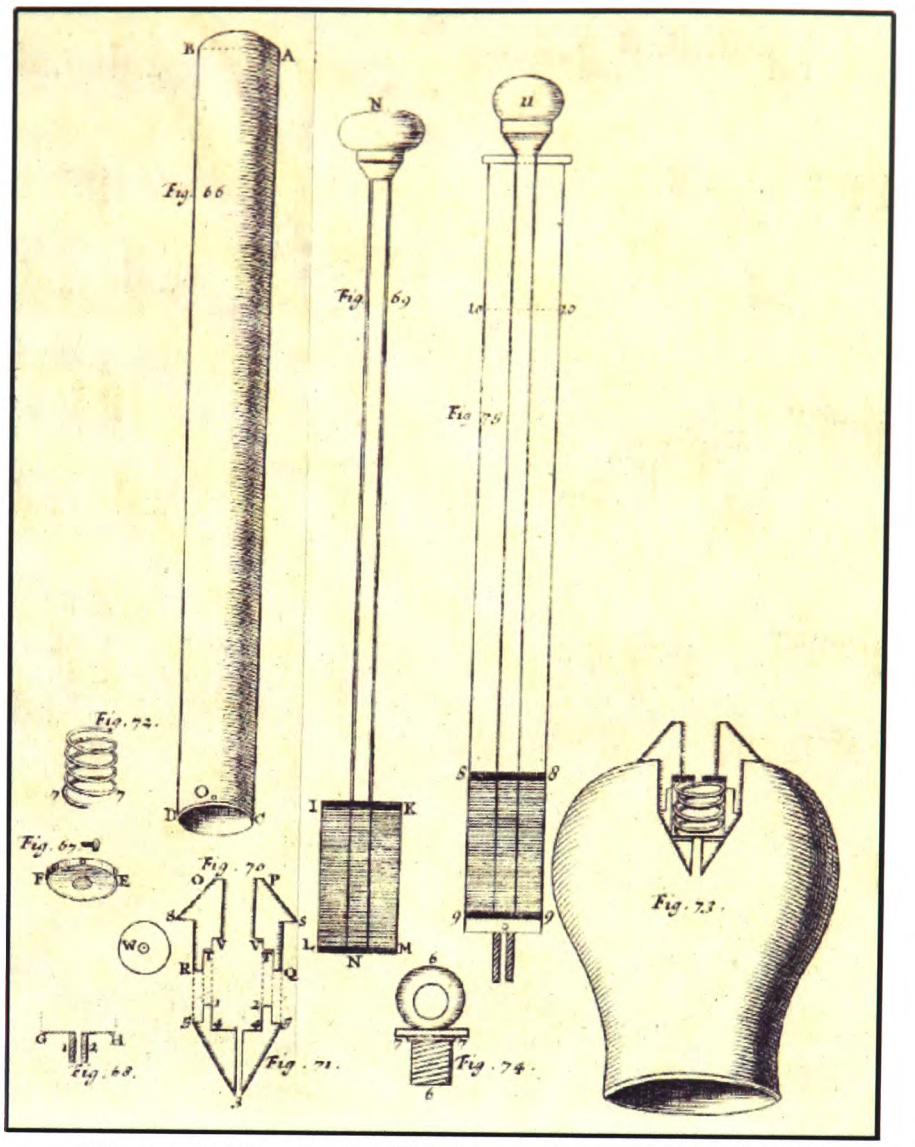



**Figure 8.** Thomas Luffkin's cupping utensils (1699). *PT*, vol. 21 (1699), 408.

### 1.1.4 Did it work?

A question that arises from reading Hauksbee's advertisements is whether or not his cupping devices would have worked in practice. If they did *not* work, the whole enterprise might have been regarded as a simple fad and Hauksbee some sort of a quack. There were many such fads in the period, and Hauksbee's advertisements were often surrounded by announcements for all kinds of medicines and 'wonder-pills'.[92] If Hauksbee's devices *did* work, however, they might represent an important link in the chain leading up to his well-known air-pump. An assessment of the claimed functions and advantages of his devices is therefore necessary.

Some of the benefits with Hauksbee's and Luffkin's concept seem obvious, for example the absence of heat. With traditional methods, there was always a danger that the patient might be scorched. If the air inside the glass were heated over a candle, or with a torch, great care had to be taken not to heat the rim excessively. If a lighted tow or paper was put into it to expand the air, the cup had to be applied quickly onto the body before the air cooled, with the consequence that hot ashes

[92] R. Porter, *The Enlightenment* (London, 2000), 79.

could fall onto the skin.[93] But with Hauksbee's method, the patient did not need to fear all this, or experience painful burning. It would become unnecessary for the operator to care for fires and lamps, or even to master the difficult task of heating and applying the glasses quickly to the skin. If a glass, on the other hand, was not hot enough, the suction effect on the skin would be insufficient, or the glass might not stick to the skin at all. Another characteristic of the traditional method was that no further control of suction, and thus the efficiency of the operation, was possible when a heated glass was placed onto the skin. To succeed with a treatment, a re-heated glass had often been applied on the same place of the body over and over again until 'no more blood will come', with the risk of burning the skin every time.[94] The efficiency of this method would therefore depend, among other things, on the pressure that was achieved inside the glasses. The actual pressure is difficult to guess, but it could not have been very low. My own estimate points to 50% of atmospheric pressure.[95] By mouth suction, however, some control of the pressure inside the glass or horn would be possible, as well as successive suction. But the lowest pressure obtainable by human suction is not very low as well, about 30% of the atmosphere.[96]

With Hauksbee's syringe, the operator had several options not found with these methods. First, he could control the pressure in the cup by the length or number of the plunger-strokes; second, he could perform controlled, successive pumpings; finally he could obtain a much lower pressure. At a later occasion, Hauksbee claims that a particular syringe could take the pressure down to 5% of the atmosphere.[97] If the cupping syringes were of a similar construction, and even though such low pressure could hardly be reached due to evaporation of humours from the skin, it would represent a major advance from traditional methods. These options would give the operator better control over the amount of blood and humours to be drawn from the skin. And in cases where repeated suctions on the same place of the skin were seen as favourable, the glasses could be left in place and simply 're-pumped'. These possibilities was pointed out early: in his second advertisement (May 1699), Hauksbee says that the pumping could be 'continued to any degree the operator finds necessary'.[98] Therefore, in contrast with the difficult and cumbersome way of cupping by heat or mouth suction, which might have taken a long time to master, this invention was very easy and convenient to use.[99]

John Harris concluded his entry on cupping in *Lexicon Technicum* with the following judgement: 'Now in England we commonly use cupping glasses without

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[93] Brockbank (1954), 82.
[94] Woodall (1639), 22.
[95] If the air in the glass became heated to 400° C, and then cooled to body temperature, 37° C. $P_1*V_1/T_1=P_2*V_2/T_2$. (Boyle's/Charles's law).
[96] A. Roth, *Vacuum Technology* (Amsterdam, 1976), 5.
[97] *PME* (1719), 15.
[98] *The Flying Post*, 9 May (1699).
[99] Brockbank (1954), 82.

fire, which is evacuated by a small syringe, (...) invented by Mr. Hawksbee'.[100] But it remains unclear to what extent Hauksbee's method reformed cupping practice. Most likely it represented a complement to existing methods, as both were regularly reported during the eighteenth century. More important is the larger progression, however, and I will later argue that this technology became transferred to the air-pump, and proved crucial to its development.

### 1.1.5 Improvements

In Hauksbee's advertisements from 1699, efficient and simple instruments that were approved by surgeons and physicians in London were exhibited. If we follow the subsequent descriptions of later announcements, however, it becomes clear that problems must have arisen, and that Hauksbee had to modify and improve his devices.

There are no preserved advertisements from Hauksbee between May 1699 and January 1701. Then, on 4 January 1701 he published a note in *The Post Man* about 'The new way of cupping'.[101] This text was very much the same as his first advertisements: Hauksbee described glasses of several sorts and sizes, applicable to any part of the body, 'which were so easy to use that any person upon sight was capable of doing it'. In addition, he was now offering a new instrument for scarifying the skin, which made 7 incisions at once, incisions less painful to the patient, and more quick and certain for the operator.[102] The most important difference, however, was a statement that the utensils 'are now being absolute perfect, and will never be out of order'.[103] This was due to amendments Hauksbee claimed he had recently made, but no details were provided. Former customers were invited to come back and get their purchases modified for 12d per engine, and 6d per glass. This shows that modifications or improvements had been made on both the glasses and the syringe. To distinguish between the old and new sort, Hauksbee described the old ones as those where the thumb is used as a valve on the engine. This suggests that the modification of the syringe consisted in eliminating the thumb-valve. The new syringes could therefore not have been

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[100] Harris (1704), under 'Cucurbitula'.

[101] *The Post Man*, 4 Jan (1701).

[102] A scarificator was a specially designed instrument that could make up to 16 small incisions in one operation. An early scarificator is described by Ambroise Paré, however only used with curing of gangrene. See: Paré (1634), 107. The earliest evidence that I have found on use of scarificators in cupping is from Hauksbee. (1701). Such scarificators were used in the Queens Bagnio in 1706, as well as in the Hummums of Covent Garden. See: B. Lillywhite, London *Coffee Houses*, (London 1963), 95-7; C. Thompson, *Love, Marriage and Romance in Old London* (London, 1936), 134; and N. Ward, *The London Spy*, (London, 1927), 167. The introduction of scarificators in cupping has often been attributed to Laurence Heister. See: Brockbank (1954), 80. The *Cambridge Illustrated History of Medicine*, (R. Porter, ed.) (Cambridge 1996), 124, describes scarificators as an early nineteenth century-device.

[103] In July1703 he proclaimed that: his utensils were 'attended with all the conveniences the Art is capable of, they being now completely perfect; nor will at any time be subject to be out of order'. See *The Post Man* 7 July (1703).

supplied with this hole. A valve using the thumb as a closing mechanism can hardly be made simpler, so the solution must have been to replace it with a fully automated one, making the use of the thumb unnecessary. No details of these changes on the cupping glasses were given. The expressions 'now being absolute perfect', and 'never out of order', sound like commercially-motivated exaggerations. On the other hand, Hauksbee admitted problems with his first utensils, and it seems that the amendments have given him new confidence. The method is no longer described as 'A' new way to do cupping, but 'The' new way, now sounding as an accepted method. He also offered his products to gentlemen living outside London, who were unable to come and see it demonstrated in person. A supplied written instruction would here be sufficient for learning the techniques.

I argue that these amendments consisted of a self-closing valve that was inserted in the piston of the pump, and an improved, self-closing one in the glasses. Hauksbee gave no details of either the old or the new valves. We know Luffkin's valve in detail, however, and Hauksbee's acknowledgments of problems only strengthen the idea that both were of a similar construction. For Luffkin also admitted problems with the valve. In addition to the syringe, the glass and the valve, Luffkin also described a stopper plug, supplied with a gasket of oiled leather. See Figure 8, *figure 74.* This could be screwed into the connector where the syringe was normally attached to stop air leaking into the glass, 'if there should happened to remain any Fissures at the valve'.[104]

Luffkin's valve consisted of five small parts including a brass spring and two pieces of leather. The weak point was clearly the spring. If it was made too hard, it would definitely help to keep the valve closed, but this would at the same time make it more difficult to open by the pressure difference obtained by suction. The result would be that the glass never would be sufficiently pumped. If, on the other hand, the spring was too soft, there would be no problems with pumping the glasses, but leaks would much more easily take place since it was too weak to press the oiled piece of leather properly towards the orifice, and shut it. Brass is not a good material for a spring either, because of its limited elasticity. Luffkin seemed to have chosen a spring that was not too hard, since he had to apply the specially made plug to stop leaks. It is clear that these utensils were not just a 'thought' invention by Luffkin, since the necessity of making a stopper could only have been the result from practical tests. But if it was a similar product that Hauksbee tried to sell to cuppers in London and in the countryside, he would most likely have got complaints. The 'Luffkin Model' would not fit well with Hauksbee's later promises of simple instruments. If such a valve, which did not always close properly, was used; then some air would leak into the glasses from the moment the syringe was removed until the stopper was in place, making a controlled operation difficult. The leaks in the valve might also increase after some time if the leather seals not were

[104] Luffkin (1749), 262.

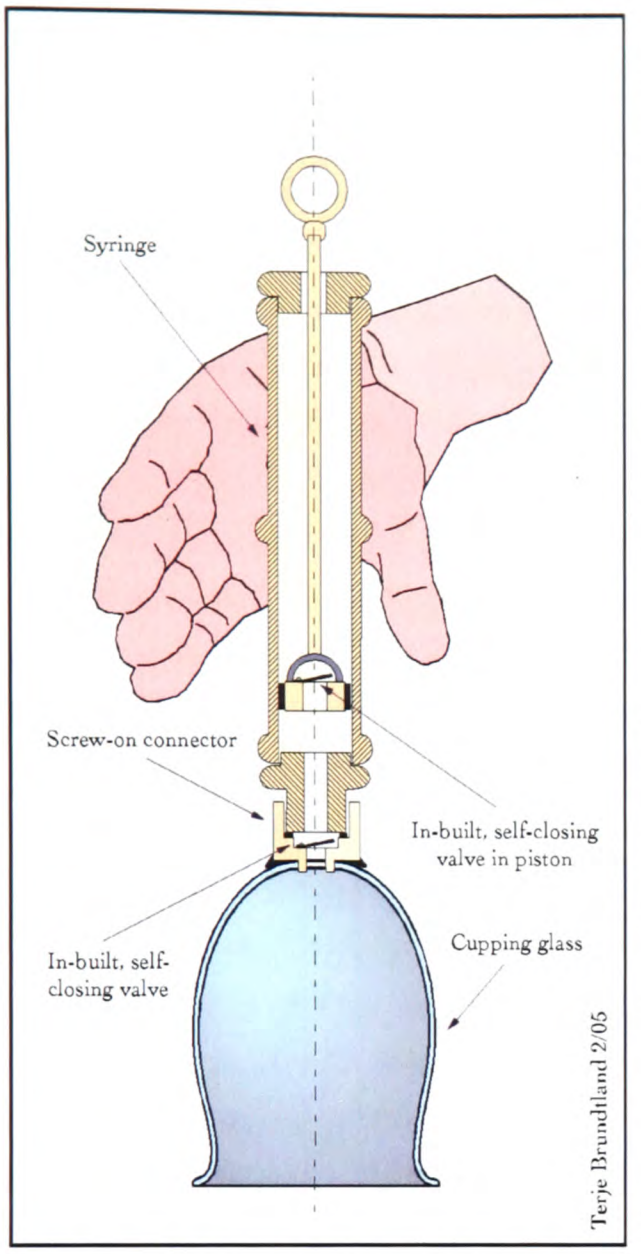



**Figure 9.** Francis Hauksbee's second cupping syringe, with automatic valve in the piston. Principle drawing.

kept wet, and the brass spring might become softer during use. Alternatively, if the spring was too hard, customers might not be able to obtain the required suction. The result in both cases would be problems with getting the glass to stick properly to the skin. Maintenance would have consisted of adjusting the tension of the spring, eventually replacing or 'lubricating' the leather seals, which required a full dismantling of the valve cones. Another disadvantage was the extra operations of screwing the stopper in and out if the same glass had to be pumped several times during a treatment, as well as being an additional component needing attention. The phrase 'never out of order', describing Hauksbee's modified cupping glass-valve must then be seen in contrast to these shortcomings. There are few hints on how it was constructed, but we know that Hauksbee later used a piece of flexible bladder-skin to cover the orifice in his valves, and it is highly probable that this solution was introduced here.

While the new valves on the glasses were more efficient than the older ones in preventing air from leaking in, the one in the sucker made the whole operation easier than before. There is little information on this valve, but it likely consisted of a flexible bladder-skin covering an orifice.[105] This flap must have covered the hole on outwards motions of the plunger, and become lifted up during inwards movements (due to differences in air-pressure over the flap) See Figure 9. It would thus pump air out of the cup by an outward stroke as usual. When the piston was moved inwards again, the air in the syringe would start to compress and the self-closing valve on the glass would close, keeping a vacuum inside. The valve in the piston would open by the same compression, however, and atmospheric air would fill the syringe and exhort further pressure on the cupping-glass valve, so that the piston could easily be moved back to the start position again.

With these new amendments, the operator had simply to screw a glass of the required size and shape onto the syringe, and then place it on the patient's skin. Holding the syringe with one hand, he could simply pull the handle of the sucker

[105] Ibid.

outwards with the other one, without having to care for the correct position of the thumb or his 'holding' hand. (Previously, the movements of the thumb had to be 'synchronised' with the movements of the sucker). When the preferred degree of suction in a glass had been obtained, the syringe could simply be moved to the next one. This was even easier than using the thumb as an opening and closing mechanism on the syringe, much easier than systems involving stopcocks, and very different again from the traditional methods by fire, lamp or mouth suction.

I argue, therefore, that Hauksbee developed these gadgets in response to complaints from customers who, having bought his first version of the cupping utensils, did not find them as reliable and easy to use as promised in his advertisements. The idea of these small components must then have been conceived sometime between the middle of 1699 and the end of 1700, and I will later argue that they became decisive features of his air-pumps.

### 1.1.6 The market

Hauksbee's cupping devices were the first practical application of the 'Vacuum Boyleanum' in England. It was also the first use of the technique in commercial products for a public market. Already at this stage, at the turn of the century, Hauksbee showed outstanding skills in vacuum-technology. The difference between the attitudes of Boyle and Hauksbee to the 'hardware' is striking. While Boyle made great efforts to describe and explain his air-pumps to the readers in text and illustrations, Hauksbee's devices were portrayed as self-explanatory. It is also clear that people at other locations, who had only read Boyle's publications, never succeeded in replicating his experiments: it proved vital to first observe the experiments being undertaken with Boyle's original equipment.[106] On the other hand, Hauksbee sold his instruments to people in the countryside by 'mail-order', where a written instruction should be sufficient to learn how to use them.[107] The tacit knowledge that had been obtained by seeing and doing air-pump experiments was no longer necessary with this level of vacuum-technology. One reason for developing and refining the technology must clearly have been Hauksbee's continual connection with his customers, including sale, complaints, improvements and then sale of modified products.

Since Hauksbee made and sold cupping utensils throughout his career, there must have been a market for such products although information about the customers is scarce. An obvious disadvantage with his method must have been the cost of the instruments. Hauksbee did not give any prices, but the syringes and the special glasses may not have been affordable to everyone in the cupping business. This points to the possibility that most customers belonged in the middle and upper classes in London.

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[106] Shapin and Schaffer (1985), 229, 30.

[107] 'Any gentleman living in the Country shall receive Directions in Writing how to keep and order the Utensils on all occasions'. *The Post Man*, 16 Aug (1701).

We know for example that cupping was among the services provided in the popular public bathhouses of London during this period.[108] There are indications that one cupping method applied in these institutions, also called 'Bagnios' or 'Hummums' (Turkish Baths), was actually the method invented by Hauksbee. In the Hummums of Covent Garden, there was a 'Man and a Woman who cup after the newest and easiest method'.[109] When Ned Ward (1667-1731) visited this place around 1700, he lively described how the air was 'drawn out' of the glasses to make them stick to his back, but without mentioning the particular method.[110] The expression 'drawn out' corresponds, however, perfectly with the operation of a syringe plunger, pulled outwards to evacuate a cupping glass. And in the Queen's Bagnio in Long Acre, men and women could be 'cupped in the best perfection, there being the best and newest instruments for that purpose'.[111] It also happened that advertisements from Hummums and Hauksbee appeared side by side in the same paper.[112] See Figure 10. While the text in Hauksbee's advertisement read: 'glasses for the new and most approved way of Cupping, (...), and the operation so easy (...)'; the one by the Hummum announced: 'cupping after the newest and easiest method'. Traditional cupping had been more or less unchanged since ancient times, so this novel cupping method that was applied in the bathhouses of London was most likely Hauksbee's invention. Therefore, the owners of the bathhouses – among them surgeons and apothecaries – could have been important customers of Hauksbee, while the bathhouses functioned as a 'test arena' for his inventions.

Most importantly the invention, production, advertising, and sale of cupping utensils, with all their advantages and disadvantages, must have provided Hauksbee with resources for developing other instruments, as well as making himself known to the public. The valves in these devices later became crucial for his air-pumps, and illustrate an effect of consumer-demand on scientific innovations.

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[108] E. Hatton, *A new view of London* (London, 1708), 784-98. Hatton lists six Bagnios in London, and describes them as places for 'Sweating, Cupping and Bathing'.

[109] *The Post Man*, 28 Sept (1706).

[110] '(...) the operator fetched in his instruments, and fixed three glasses to my back, which, by drawing out the air, stuck to me as close as (...)'. See: Ward, (1927), 167.

[111] T. Mapleson, *A treatise on the Art of Cupping* (London, 1813), 27. One of these instruments were the scarificator, see note 102.

[112] *The Post Man*, 10 Oct (1706).

Bank 79 and 2 qr, Sword Blades 9 and a qr, Mine Shares 21 and a half, New Company and Shares no Transfer.

The Court of Directors of the Governor and Company of the Mine Adventurers of England give notice, that the Annuities taken in lieu of the Principal Money originally adventurered will begin to be paid on Thursday the 17th inst. and for that purpose attendance will be given at their House in Angel Court on Snow Hill, every Tuesday and Thursday from 9 to 12 in the Morning, and 3 to 5 in the Afternoon.

MR Tutchin, the Author of the Observator, does hereby give notice to all Gentlemen that have occasion to write to him, that they direct their Letters to Mr. Benj. Bragg at the Raven the corner of Pauls Alley in Paternoster-Row, and no other place.

AT THE HUMMUMS IN COVENT-GARDEN *are the best Accommodations for Persons of Quality to Sweat or Bath every hour in the year, the conveniencies of all kinds, far exceeding all other Bagnio's or Sweating Houses both for Rich and Poor. Persons of good Reputation may be accommodated with handsome Lodgings to lye all night. There is also a Man and Woman who Cup after the newest and easiest method. In the Garden of the same House is also a large Cold Bath of Spring Water, which for its Coldness and Delicacy deserves an equal Reputation with any in use.*

A Messuage near Ruthy Green in the Parish of

Sheer-lane near Temple Bar, and at Royce's Coffee-house in Clare Market, at 1 s. a Paper, where Directions may be had at large.

AIR *Pumps, both single and double Barrell'd, with Apparatus for making the many Experiments demonstrating the several Properties of Air; as its Pressure, Spring and Elasticity. The Effects of its absence on the Lives of Animals, Sound, Flame, &c. having Mercurial Gages adapted to 'em, shewing at all times the degrees of Rarefraction to the greatest nicety. Engins for Condensing Air, small Air Pumps applicable to Glasses for the new and most approved way of Cupping. The Glasses are of several forms and sizes suitable to any part, and the Operations so easy, any Person upon sight is capable of them. Scarrificators, one of which at once makes 10, another 16 effectual Incisions, Hydrostatical Instruments for finding the Specifick Gravities of Liquids and Solids with Ease and Accuracy. Syphons and Blow-Pipes with Valves for Anatomical Injections. All which according to their latest Improvements, with directions how to use and order on all occasions, are sold only in Wine Office Court in Fleetstreet, by Fr. Hauksbee Author of'em and F.R.S. being lately remov'd from Giltspurstreet without Newgate.*

THE finest Lucatellus Balsam that ever was made in England, to which is now added, the true *Balm* of Gilead and 3 or 4 other rich Balsamicks, which makes it a noble and efficacious Medicine in all inward Straines, Soreness, Bruises, Pleuritick Pains, Ulcers of the Lungs or any inward part, Coughs, Hoarseness, shortness of Breath, spitting of Blood, or bloody Flux, it relieves Pains in the Kidneys, thro. Stone, Gravel or sharpness of Urine, causing the Water to slide away easily Taken at night going to bed it eases Tickling Coughs wonderfully and gives Rest; 'tis of such a soft healing Nature, it Cures Chapt Nipples, Lips and Hands presently, making them smooth and soft, and Cuts and green Wounds it helps in 48 hours. The Author has left it to be sold only at Mr John Howe in Talbots Court in Gracechurch-street, Mr Smith's at the Post Office in Covent Garden, and at Cambridge by Mr Alphs, at 1 s. a Pot with Directions, each Pot being now (and will always be) seal'd with the Author's own Seal, the Sun Flower, Mantle and Crest; if not, 'tis a Counterfeit.

**Figure 10.** Cupping advertisements. *The Post Man*, 10 October 1706. The parallels between the Hummums (right) and Hauksbee's attention to cupping methods are underlined.

## 1.2 The new engine

Hauksbee was a keen advertiser and he presented his products at least 25 times from January 1699 to July 1703 in *The Flying Post, The Post Man, The Gardener's Almanack,* and *The Double Ephemeris.*[113] In January and May 1699, and from January to September 1701, Hauksbee's main concern had been to make his excellent cupping utensils known to the public. In November 1701, however, an important new item was added to the product list:

> Also an Engine which serves as an Air-pump for making experiments in Vacuo, performing them with ease and exactness, without the use of Cement or Stopcock. The same Engine to be used for compressing air to the greatest violence, and Likewise is a siringe for the injection of Wax, Mercury or Air in Anatomy, with other qualifications beyond any Instrument yet made for that purpose.[114]

I will here describe this engine and show how it served as a transition from the cupping syringes to air-pumps and other instruments. It is clear that this contrivance was a move towards the product range that would become typical for him, including cupping utensils, air-pumps, condensing engines (air-compressors), and anatomical injectors. The 'new engine' is important for our understanding of Hauksbee as an instrument-maker for several reasons. First, it is the earliest known evidence of Hauksbee's production of air-pumps, an activity that made him a key figure in the history of early vacuum-technology. The device represents also the beginning of a commercialisation of air-pumps in England, as well as the first sign of Hauksbee's activities within experimental philosophy. It also points to his engagement with condensing engines and anatomical syringes.

A reconstruction of the size and functions of the multi-purpose engine is necessary to understand its role as a predecessor of Hauksbee's air-pumps and other instruments. Although little information could be found about it apart from advertisements, a reasonably good picture may still be achieved.[115]

### 1.2.1 Size and form

Hauksbee described the engine as an apparatus that could serve as an air-pump capable of making experiments in vacuum with 'ease and exactness', and 'without the use of cement or stopcocks'. These characteristics later became part of the standard-description of his air-pumps. The same device could also compress air 'to the greatest violence', as well as work as an injector of wax, air and mercury in anatomy. What sort of device this was becomes clear as he described it as a

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[113] *The Flying Post: or, The Post-Master* (London, 1699); *The Post-man, And The historical account etc.* (London, 1699-1706); G. Kepar, *The Gardener's Almanack for the Year of our Lord 1702* (London, 1702); G. Parker, *A Double Ephemeris for Year of our Lord 1703* (London,1703).

[114] *The Post Man,* 13 Nov (1701).

[115] Some information on Hauksbee's personal development and role in society might also be extracted from these advertisements, a topic that however, will be discussed in Chapter 2.

'siringe', when it was used for injections. This was in fact the first time Hauksbee explicitly stated that he was dealing with syringes, but as I have shown, the key component in his previous advertised cupping utensils was just such a device.

The novel engine could not have been a simple cupping-syringe applied for a new purpose, however. This is evident from the nature of its various functions, for example the possibility of making experiments in vacuum.[116] Hauksbee had earlier underlined that the cupping syringes were small engines, which of course would be sufficient to evacuate the relatively tiny volumes in the cupping glasses. A hand-held syringe of small size and low weight would also be the most convenient to use for the operator, as well as for the patient. But most of the classical vacuum-experiments required a volume much larger than a cupping glass, for example the spherical receiver on Boyle's first air-pump contained 30 wine quarts, or about 35 litres.[117] It is most likely that Hauksbee already used large receivers at this stage, especially since he described the new engine in the same terms as his later separate pumps (which had large receivers). And since he underlined that the experiments were easy to make, the time for evacuating the receiver and preparing a new experiment must have been reasonably short. A cupping syringe would not have been satisfactory for the task.

Surviving early-nineteenth-century cupping syringes and glasses are found to be about 50 and 100 $cm^3$, respectively.[118] If we assume that the size of cupping glasses and hand-held syringes did not change considerably during the eighteenth-century, these values are also valid for Hauksbee's models. To evacuate a cupping glass down to a pressure suitable for experiments with a hand-held syringe would be manageable in a few seconds, for example achieving 5% of atmospheric pressure would require seven strokes.[119] But if a receiver, big enough for holding apparatus for vacuum experiments were evacuated with such a syringe it would take a very long time. Hauksbee didn't say anything particular about the experiments or the size of the receiver here, but if we assume it was of size similar to those given by Harris, some calculations can be made. Hauksbee's first air-pump (Figure 6) was supplied with a barometer, and the natural length of such a scale is 29.5 inches or 76 cm. If we assume that the components of the pump were all drawn approximately to the same scale, the receiver volume can be worked out. Using the barometer as a 'measuring rod', the receiver (R, [Hauksbee's first air-pump] in Figure 6) is approximately 35 cm high and average 20 cm in diameter, giving a volume of approximately 11 litres. The other receiver, (R.2) comes out with about 10 litres. Should an ordinary cupping syringe with a volume 50 $cm^3$ be used for

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[116] This shows that experiments in vacuum were on Hauksbee's agenda already at the end of 1701.

[117] *Boyle's Works*, i, 160-1.

[118] Based on instruments held in The Museum of the History of Science, Oxford.

[119] Boyle's law: $\mathbf{p_n = p_0\left(\frac{v_r}{v_r + v_s}\right)^n}$ where $\mathbf{p_n}$ is the pressure in the receiver after $\mathbf{n}$ number of strokes, $\mathbf{p_0}$ the original pressure (normally atmospheric), $\mathbf{v_r}$ the volume of the receiver, $\mathbf{v_s}$ the volume of the pump-barrel or syringe.

evacuating a receiver of 11 litres or 11000 $cm^3$ to a pressure of 5% of the atmosphere, more than 650 strokes, and 20-30 minutes pumping time, would be required. (20-30 strokes or pulls per minute.) Experimenting should be easy according to the text, so this is far too long a time, both for onlookers to wait during demonstrations, and very fatiguing for the operator. On the other hand, if a recipient of 11 litre should be evacuated to the same pressure as above, for example in 5 minutes, (25 pulls pr minute), a syringe volume of 270 $cm^3$, would be required. This is within the same order of size as extracted from the pump-barrel on the engraving in *Lexicon Technicum*. See also section 1.3.1.1. The fact that the quantity of material injected in pathological specimens was normally much larger than what could be held by a cupping-syringe also indicates that the new engine was considerable larger.

Therefore, the multi-purpose engine had to be a syringe of comparable size to the barrel of Hauksbee's separate air-pumps and siphons, which came later. It could not have been a cupping syringe used for a new purpose.

### 1.2.2 Functions

To be able to combine an air-pump, compressor and injector into one instrument, some major alterations had to take place to allow transformation from one application into another. Since the engine could be used as an air-pump that worked without stopcocks, there must have been some sort of automatic valve in the piston. Other arrangements, for example the thumb-valve principle of Hauksbee's early cupping syringes seem unlikely to have been used here. A barrel or syringe of this size required normally a two-handed operation for pulling, which would make using the thumb as a valve impossible. This would also require an additional stopper for closing the thumb-hole when used as a compressor, which must have been an inconvenience. Should a piston-valve be functional here, it had to close when the plunger was pulled outwards and open when it was pushed inwards, in fact similar to the valve of the cupping syringe. But a piston like this would not have served any purpose if the engine became used for compressing air. Such a piston had either to be solid with no valve in it at all, or it could be supplied with a valve that was mounted in a way that opposed the valve in the air-pump. A valve like this had to close on the inward strokes, and open on the outwards. Such a syringe, convertible from a simple air-pump to a condensing engine by turning the piston upside-down is in fact described by John Desaguliers (1683-1744) who, among other things, continued Hauksbee's lectures in natural philosophy.[120] If the syringe should be applied for injecting air, it simply had to be arranged like the compressor. A solid piston was, however, required when it was used for injecting wax or mercury. It could be filled by either holding it upside-down with the cannula removed, pouring the material into it, or suck the actual substance into the

[120] J. Desaguliers (1744), 390; plate 21, Fig. 11; and plate 24, Fig. 5, 6.

syringe through the cannula by an outward pull of the plunger. The wax or mercury could then be ejected, out through the cannula, by pressing the solid plunger inwards. The practicality of these methods must have been dependent on the viscosity of the substance, as well as the bore.

Since these relatively different functions were possible with the same engine, the main component must in fact only have been the syringe-cylinder itself and the plunger-rod – something similar to the cupping syringe, but bigger. A few different pistons were required, as well as several front end-pieces that could be fastened to the barrel, making it connectable to various external apparatus. The user of the engine must have been able to connect it to a receiver for vacuum experiments through a component containing another valve, or perhaps to a cylinder or spherical-shaped metal container for confining the pressurised air – as well as supplying it with a cannula to transform it into an injector.

To alter the function of the syringe could not have been very difficult for a trained experimenter, but it must have taken some time, especially if cleaning was necessary. To convert the engine from one function to another, the syringe had first to be disassembled and the equipped piston removed and replaced with the correct one. If the syringe had been used as an injector and for that reason had been filled with a substance, cleaning must also have been required. After cleaning and replacing the piston, the syringe had to be assembled in the reverse order. The idea to use a single engine as a combined air-pump, compressor and injector seems rather clever, but must have been difficult to use in the long run. Repeated alterations would also create wear on threads and gaskets, increasing possibilities for leaks and breakdowns, such inconveniences could have been a reason for developing the instruments further. The multi-purpose engine was advertised for a last time in April 1703, and disappeared then from the product range. Nonetheless, Hauksbee's planning, manufacturing and sale of this engine with its external apparatus was one step away from the cupping utensils and towards a more sophisticated range of instruments with separate air-pumps, condensing engines and medical injectors.

## 1.3 Separate instruments

After the 'multi-purpose' engine had been available for about a year, it got competition from two other instruments capable of similar functions. In October 1702, Hauksbee modified the advertisement-text to include:

> Also Air pumps, with Apparatus for making all manner of Experiments proper to be made in Vacuo Boyliano, with ease and exactness, without the use of Cement or Stopcocks; Likewise Syphones for injections in Anatomy, with other useful qualification beyond any Instrument yet made for that Purpose, also Blow Pipes with valves for the same use. [121]

According to this announcement, Hauksbee offered separate 'air-pumps' (plural) for sale, including apparatus for making all sorts of experiments in vacuum. The air-pumps were described in the same terms as the 'air-pump mode' of the combined engine, as Hauksbee proffered that they could perform experiments with ease and exactness, and without cement and stopcocks. He also offered separate siphons and blowpipes for anatomy-injections.[122] There is a close relationship between Hauksbee's cupping utensils and his air-pumps, condensing engines and injectors. I have shown above how the combined engine served as a transition from the small cupping devices to the larger instruments. Here I will show how Hauksbee's experiences in making, for example, air-tight seals, screw-on connections and valves for the cupping utensils and the combined engine became crucial for the success of his separate instruments.

### 1.3.1 The first air-pump

The origin of Hauksbee's air-pumps has been the subject of numerous speculations. Here I argue that his first separate pump was put on the market in October 1702.

The best contemporary account of this pump is given in the 1704 edition of *Lexicon Technicum,* containing an illustration and a textual description. Although this work was published in 1704, it clearly depicts and describes the pump as it was in 1702, or even earlier. This is clear because all of Hauksbee's instruments that were shown in the illustration (Figure 6) were also mentioned in Hauksbee's advertisements of October 1702, while Harris also described the instruments in terms similar to those in the advertisements. Also, of course, the entry in the *Lexicon* must have been written some time before it was published. Furthermore, there is in fact no difference between the description of the multi-purpose engine of November 1701, when used as an air-pump, and his first separate air-pumps of October 1702. The only major addition was a range of pump-appurtenances for

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[121] The Post Man, 27 Oct (1702).

[122] Separate engines for compressing air were advertised from September 1705 and onwards.

making experiments in vacuum. This all points to the conclusion that Hauksbee's air-pump concept was developed already in 1701.

Hauksbee's first air-pump is depicted in Figure 6. It consisted of a single barrel or syringe (S), mounted horizontally under a square board (A, B, C, D), which also supported the vacuum-recipient, (R). The pump was supplied with a mercury barometer (G) attached under the pump plate for monitoring the pressure inside the recipient. Another glass-receiver (R.2.), and a cupping glass, (F) is also shown.

#### 1.3.1.1 Volume and shape

Like the cupping-glass and the pump recipient (having a volume of 100 versus 11000 $cm^3$), the greatest difference between the cupping syringe and the pump-barrel was size. Using the same method as is described on page 55, an estimate of the size of the barrel (S) is more difficult since it is drawn in a slanted position. I will estimate the length to about 35, and the diameter to 3 cm. This corresponds to a volume of approximately 0.25 litre, and pumping would have required a pull of about 7 kg in each stroke. The shape of the handle (H), which is a transverse two-hand grip, suggests a force of this order as well. This air-pump, which in turn was the basis for the double-barrelled one, will be subjected to a comprehensive study in Chapter 2

Except for the size, there are many parallels between Hauksbee's cupping-concept and his air-pump. First, the function of the cupping-glass and the pump-recipient was more or less identical. Both were used to confine the vacuum that was created by a pump and to supply a space for the objects in question - either the sick blood or the item subjected to air-pump experiments. Second, both were made of glass, which gave the operator possibilities to see and control the various phenomena, an important advantage compared to opaque cupping-horns and Guericke's solid copper spheres. Another resemblance was the shape. Early vacuum-receivers were often depicted with the form of large cupping glasses, for example those by Robert Boyle.[123] Christian Huygens described some of his receivers as shaped like cupping-glasses.[124] A practical difference was that the cupping glass was pumped through a valve attached to the top, while the air-pump receiver was evacuated from below by a hole in the board. Most of the earlier air-pumps used a similar arrangement. For Guericke, for example, this concept was based on the belief that the air would drop out of the receiver by it own weight.[125]

These parallels are even more evident with the cupping syringe and the pump-barrel. In spite of different dimensions, both the multi-purpose engine and the horizontal barrel on Hauksbee's first air-pump were in fact large syringes.

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[123] *Boyle's Works*, vi, 115.
[124] C. Huygens, D. Papin, 'Some Experiments Touching Animals', *PT*, vol. 10 (1675), 547.
[125] Helden (1991),157.

### 1.3.1.2 Leak-tightening

It was not only the shape and the pumping-principle that was related. Another connection is the way Hauksbee solved the sealing issues on his air-pump. Hauksbee underlined in all his advertisements from 1701 to 1703 that the air-pump experiments could be performed 'without the use of stopcocks or cement'. What the absence of cement on Hauksbee's pumps meant in practice becomes clear from Harris's account. This description makes it clear that the recipient (receiver) could easily be secured to the square board, which for example could be fixed to a table or in a windowsill. In the middle of the board, however, there was:

> a hollow which contains a Brass Plate, on which the Recipient R is placed and fastened to it without any cement, by means of a thin piece of wet leather.[126]

This implies that when the bell-jar was evacuated, the weight of the external air would press it downwards, and consequently its rim into the wet leather, which would make a perfect seal that stopped air from leaking in. Hence, no cement was needed to glue and seal the recipient to the board. Earlier air-pump makers had used cement to prevent leaks between the bell-jar rim and the plate, and on other joints, but it had proved to be a difficult issue. In addition to being a product description, the statement about the lack of stopcocks or cement in the announcements can also be seen as a sales promotion for signifying the qualities of the pump. It seems to be written for contrasting the operation of previous air-pumps, for example those by Robert Boyle, which were strongly dependent on such components and materials.[127] This suggests that Hauksbee, among other issues, was targeting a public with knowledge of older air-pumps.

It is obvious that Hauksbee must have worked with difficult leak problems before he started to make air-pumps. He must have been familiar, for example, with gaskets and leak-tightening problems from his production of cupping utensils. A gasket of leather or other soft material must have been ideal to use in the connector on the cupping syringe, and in the mating one on the glass, to prevent leaks. Cement would have been too cumbersome and time consuming for the operator since the syringe could be removed easily and applied on another glass. Also, the syringe itself had joints where a leather seal would have been favourable, for example in the connection between the cylinder and the glass-connector (Figure 9), and also between the piston and the wall.

Another example is found with the special-shaped cupping glasses that Hauksbee advertised in 1699. Now he offered glasses that could cup a whole finger or toe in one operation. These cups must have been shaped like narrow cylinders, unlike the common ones, but with a similar connection for the syringe. Such an arrangement would have required special sealing gadgets to close the opening

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[126] Harris (1704), under 'Air-pump'.
[127] See Chapter 2.

between the rim of the glass-cylinder and a finger or a toe. This had to be flexible and airtight, if the method were to work well. The most natural thing to use here must have been a piece of leather or another suitable, soft material, with a hole for the finger/toe in the middle, and wide enough to cover the cylinder rim. Some soft cement or sealing wax might have been applied between the finger/toe and the leather, and between the glass and the leather, to make the joints more flexible, and to stop smaller leaks. Cement alone, however, could not have been sufficient because of the distance between the glass rim and the finger/toe, and the fact that the patient would inevitably move the finger or toe a little during the treatment. Hauksbee did not mention these special glasses in particular after May 1699, but they were most likely included in the description: 'The glasses are of several Forms and Sizes Applicable to any part', which he used in a later advertisement.[128] In any case, problems with making functional glasses for cupping fingers and toes must have made him concerned about sealing techniques, for example how to pick the right sort of leather, and how to treat it for making the best seals. This practice must again have given him a good background for dealing with similar challenges with air-pumps.

#### 1.3.1.3 Connectors

One necessary condition for Hauksbee's multi purpose-engine to be functional was that it could be easily connected and disconnected to different kinds of apparatus. A system with reliable air-tight connection gadgets must consequently have been developed, and the separate air-pump required a similar connection system.

Leaks in the various joints, as well as around the receiver rim had been a serious problem for the first air-pump makers, and many efforts had been made to solve the problem. Not only for making the pump into an efficient and reliable research tool, but also to get the pump accepted as such by other natural philosophers.[129] How to make leak-tight joints was a problem that Hauksbee had worked on earlier, when he developed the system where one syringe was used with several cupping-glasses. The small syringe had to be connected to the cupping glasses by a simple, leak-tight connector, most likely a screw-on type or something of that sort. After finishing pumping, the syringe had to be removed, and mounted on the next glass easily. With Hauksbee's first air-pumps, the barrel was attached to the brass plate under the receiver by means of a 90° elbow-connector, a method that required two leak-proof, screw-on/screw-off joints. The only difference between this connection and the one that connected the small syringe to the cupping glass was the shape (a curved versus a straight connector-piece). A cross-section of the Hauksbee's first air-pump is given in Figure 11, where the 'internals' are reconstructed from the text.

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[128] *The Post Man*, 2 Jan (1701).
[129] Helden (1991), 162.

Therefore, Hauksbee's ability to make functional and reliable connections between the receiver and the air-pump barrel was founded on experiences gained from cupping utensils as well as the combined engine.

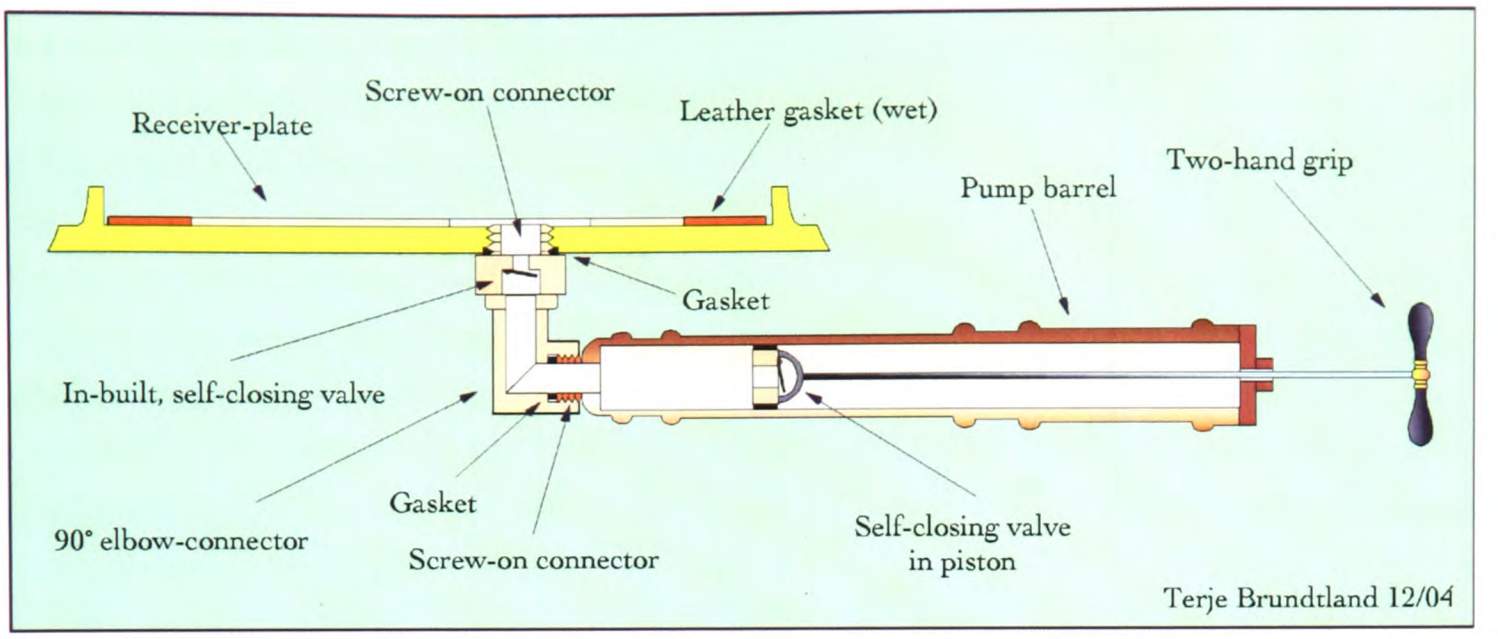



**Figure 11.** Cross-section of Hauksbee's first air-pump. Based on text and illustration in Harris (1704) and my findings about the cupping utensils discussed above. Compare with Figure 6 and 9.

### 1.3.1.4 Blood and mercury

One important characteristic of the multi-purpose engine, when applied as an air-pump, was the attached barometer. The existence of such a facility can be derived from the term 'exactness' in the advertisements, and can be seen, like the phrase 'without cement and stopcocks' as both a product description and a sales promotion written to distinguish them from Boyle's pumps. The in-built barometer on the separate pump is evident from Harris's description.

I shall here show how close the principle behind Hauksbee's barometer was to a cupping-phenomenon, and argue a connection between the two. Hauksbee's barometer was mounted below the receiver-board, with the open end connected to the receiver. The reservoir was open to the atmosphere, and the vacuum monitored by the length of the mercury-column in the tube, forced upwards by the difference between the atmosphere and the receiver-pressure.[130] The elevation of mercury corresponded to the degree of vacuum in the receiver, and acted thus as an indicator of pump-efficiency as well as an indicator of the quality of the sealing, and of the general preparations of the experiment.

With cupping, the amount of blood that was flowing into the glass must have been a similar indication of how well the utensils worked and were applied. There are many parallels between Hauksbee's cupping utensils and his air-pumps and this is yet another example, since both the elevation of mercury and flow of blood worked by the same physical principles. Both liquids were forced from one place to

[130] An extensive discussion of Hauksbee's air-pump barometer follows in Chapter 2.

another by pressure differences, the mercury by the atmosphere versus the vacuum in the receiver, the blood by the internal pressure in the flesh versus the vacuum in the glass.

For a trained cupper, or air-pump operator, the amount of blood or the level of mercury must have been a clear indication of how well the equipment worked and had been set up. For a cupper this would include the function of the syringe, the effectiveness of the valves and absence of leaks in the connector, as well as whether the glass had stuck properly to the skin or not. For an experimenter, a high mercury level would have signalled an efficient pump and a well-prepared experiment, a low mercury level would have indicated possible leaks in the pump, malfunctioning valves or insufficient sealing around the receiver-rim. The usefulness of Hauksbee's in-built barometer was confirmed by Musschenbroek in Holland in 1711, who, according to Z. Uffenbach, planned to supply his own pumps with such 'tubo mercurii'.[131]

The similarities between the use of the 'flow of blood' and 'rising of mercury' as indicators are so arresting that I see the cupping phenomenon as a model for Hauksbee's barometer concept.

### 1.3.1.5 The air-pump valve

Another feature of Hauksbee's air-pump was the absence of stopcocks. Boyle had used manual stopcocks on his pumps to connect or disconnect the receiver from the barrel as the sucker was moved in and out.[132] But such components were unnecessary already with Hauksbee's engine from 1701 when it served as an air-pump, and as I have shown in section 1.1.2, there is nothing indicating that Hauksbee supplied his cupping glasses with stopcocks to close them off. Instead, small valves did this automatically, which made cupping by syringes a relatively easy task.[133] That valves were crucial components in Hauksbee's first air-pump also, comes clear from Harris's description:

> In this Brass plate are two Holes into one of which is an Elbow fitted, which hath the End of the *Air pump* screw'd on it, and on that Screw is a Valve made by a piece of a Bladder, and answers alternately to another in the Sucker, opening when that shuts, and closing when that opens reciprocally.[134]

There were hence two valves in this air-pump, one in the elbow below the brass plate, the other in the sucker of the syringe. They were arranged so that when one opened, the other shut, and vice versa. If a system like this were to work, the valve

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[131] Z. Uffenbach: *Merkwürdige Reisen durch Niedersachsen Hoölland und Engelland*, (Ulm, 1754), 430. See: Peter de Clercq, *At the sign of Oriental Lamp. The Musschenbroek workshop in Leiden, 1660-1750* (Rotterdam, 1997), 109 and 282, note 18.

[132] *Boyle's Works*, i, 157 (the first air-pumps); and vi, 36 (the second pump).

[133] The fact that Papin's double-barrelled air-pump was supplied with self-closing valves, and a possible influence from this on Hauksbee's apparatus will be discussed in Chapter 3.

[134] Harris (1704), under 'Air-pumps'.

in the elbow had to open when the plunger was pulled outwards, while the valve in the sucker had to stay shut. The pressure in the receiver would be reduced since the total volume (the receiver volume plus the syringe volume) was increased by the outward motions of the piston. The elbow-valve would shut and seal off the receiver by an inward motion. At the same time, the valve in the sucker would open, releasing the evacuated air from the receiver into the atmosphere and making it easy to push the piston inwards to the start position again. (See Figure 11). But it is evident that the working principle and function of these valves were exactly the same as those introduced as amendments in Hauksbee's cupping-glasses and syringes in January 1701. These changes consisted in inserting a reliable one-way valve in the screw-on connector on the glasses and one in the syringe-piston, so that the valve in the connector-piece opened, and the one in the piston closed on outwards movement of the plunger, and vice versa. But these are exactly the same functions that Harris assigned to Hauksbee's air-pump valves. The valve in the 'screw' on the 90° elbow answered to that in the connector on the cupping glass, and the valves in the pistons of both the cupping syringe and the air-pump barrel had identical functions. In the air-pump, the valve was made from a piece of bladder, a concept that Hauksbee could have developed when he improved his cupping utensils. The contrivance he had made at that time, most likely initiated by complaints from users of his earlier models, had made him confident enough to claim that his cupping utensils 'never would be out of order'. It must have been the experiences from that undertaking that made up the concept of the air-pump valves.

There is little evidence on Hauksbee's cupping engagement except for the newspaper advertisements and *Lexicon Technicum*. In an originally unpublished letter from Stephen Gray (1666-1736), however, we find a short note that demonstrates the relationship between the new way of cupping and Hauksbee's air-pumps. Gray was a contemporary of Hauksbee who worked primarily with electricity, but was never granted the same favour in the Royal Society. In this letter, which contains several comments on Hauksbee's electrical experiments, Gray proposed a new cupping device made by a small drinking glass with the foot removed.[135] Breaking off the foot would create a small hole in the bottom of the glass and, by cementing a short tube into it; the glass could serve as a cupping device via mouth suction through the tube. However, to be able to keep the vacuum in the glass while the operator 'took breath', Gray mounted a valve 'like those in the 'Haukesbeean' air-pumps' on the top of the tube. The external air would here shut the valve between the breathings.

Gray's cupping concept was a mix between the traditional cupping by mouth-suction and Hauksbee's syringe system. The valve corresponded to the one in the

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[135] R.A. Chipman, 'An Unpublished letter of Stephen Gray on Electrical Experiments, 1701-1708', *Isis*, vol. 45, no. 1 (May, 1954), 33-40. Chipman comments on the entire letter, except for the note on the cupping device.

connector on top of Hauksbee's cupping glass, the mouth suction to the effects of the syringe. The reason for not developing this idea further was explained by his remoteness from the 'Glass house'. Gray's proposal must anyway be seen as an attempt to challenge Hauksbee's concept of cupping utensils.[136] It demonstrates that both cupping and air-pumps, and especially Hauksbee's valves, were seen as related, and that they were on the agenda for experimental philosophers at the time.

### 1.3.2 The condensing engine

Hauksbee's separate air-pumps and injection siphons were introduced in 1702, but no separate condensing engine was advertised before September 1705.[137] I will, argue that the concept for such a device was already developed with the combined engine of 1701. A short survey of Hauksbee's work with pressurized air is helpful for understanding his status prior to the engagement with the Royal Society.

Hauksbee is well-known for his work with air-pumps, but he also performed series of experiments with condensing engines, for example his studies regarding the propagation of sound through compressed air.[138] He also produced and sold equipment for such experiments throughout his whole career. In contrast with the air-pump, however, little attention has been paid to the origin of his condensing engine. Hauksbee's air-pump and condensing engine had practically the same root, as both started as different applications of the multi-purpose engine. The main component of this instrument was its large syringe, but the statement 'for compressing air to the greatest violence' in the advertisement of October 1701 definitely implies more than that. To perform experiments with pressurized air, the air must first be compressed to a much higher pressure than is possible through a single stroke of a plunger. If the statement were to be meaningful, some sort of a container or tank where the compressed air could accumulate from repeated plunger-strokes was therefore necessary. The container had to be supplied with an arrangement to connect and de-connect the syringe easily, (since the syringe could be used for other purposes too), as well as a stopcock to close it off for keeping the pressurised air inside. During experimentation, the air had to be released in a safe and controllable way, presumably through the same stopcock. An automatic valve between the syringe and the container, like that in the air-pump arrangement, would not have been useful here. It is therefore clear that by November 1701, Hauksbee had constructed, in addition to the large syringe, a container for keeping the accumulated and pressurised air, a release mechanism, (for example a stopcock), and some instruments for displaying the effects.

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[136] The possibility that Hauksbee might have stolen ideas from Gray, especially concerning electricity, is discussed in: D. Clark and S. Clark, *Newton's Tyranny* (New York, 2001).

[137] *The Post Man*, 27 Sept (1705).

[138] *PME*, 125-9.

Thus, it may not be a coincidence that Hauksbee's first article in the *Philosophical Transactions*, of April, 1704, was about an experiment in which he simulated 'the falling of the barometer in a storm'. In this experiment, clearly inspired by the devastating storm over southern England on 26-27 November 1703,[139] pressurised air from a spherical container was released through a tube and acted as a strong wind in a barometer assembly.[140] As a result, the mercury in both barometers sank. See Figure 12.

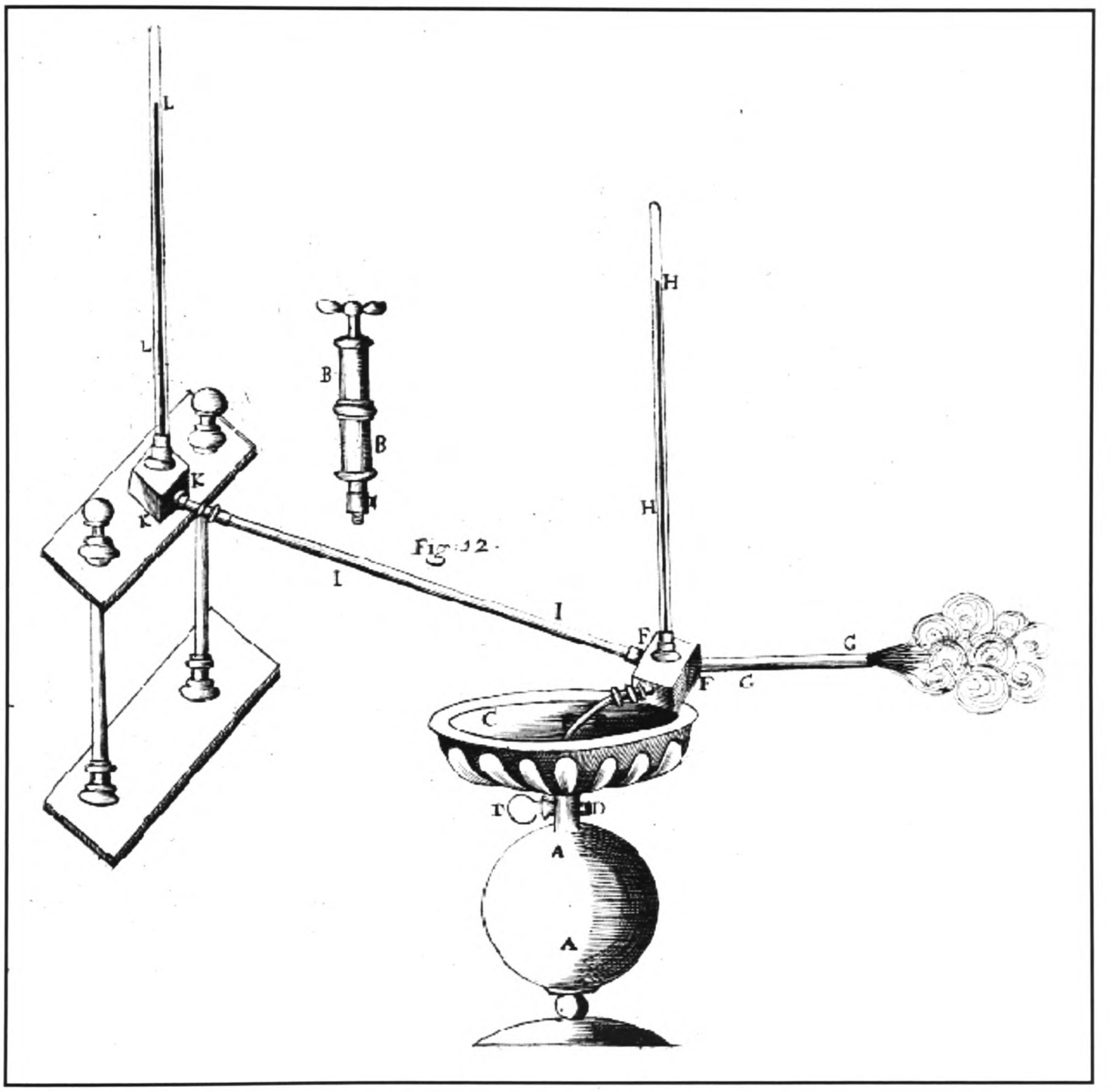



**Figure 12.** Hauksbee's storm-experiment. This was published before the separate condensing engine was put up for sale (Sept, 1705), so the syringe depicted (B) is most likely the multi-purpose engine. Also two barometers are shown (L and H), as well as a spherical container for pressurized air (A) with a stopcock (D). The small stud at the lower end of the syringe is a male screw-on connecter for attachment to the stopcock on the inside of the basin C. It was also used when the syringe was applied as an air-pump. The stud protruding to the right must have been used when the syringe was used as a siphon (see section 1.3.3). *PT,* vol. 24 (1704), 1629-30.

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[139] M. Brayne, *The Greatest Storm* (Sutton Publishing, 2003).

[140] F. Hauksbee, 'An Experiment, to show the Cause of the Descent of the Mercury in a Storm', *PT,* vol. 24 (1704), 1629-30.

However, similar components to those used for this experiment – including the barometers - must already have been available in November 1701. When used as an air-pump, the multi-purpose engine was, for example, equipped with a barometer (see above). Hauksbee's general acquaintance with barometers in this period is also confirmed by an advertisement from October 1702, where he announced that he had a large, sophisticated mercury-barometer on display in his workshop (Figure 6).[141]

It is also clear from other sources that Hauksbee's instruments for pressurized air became available early. In 1704, William Derham undertook tests with pressurized air on animals, using Hauksbee's equipment, This is, moreover, the first known experiment where an actor different from Hauksbee himself used Hauksbee's apparatus.[142]

When Hauksbee came to the Royal Society in December 1703, he must already have gained experience in manufacturing and utilizing high-pressure equipment.

### 1.3.3 Injectors, siphons and blowpipes

Francis Hauksbee Senior's engagement in anatomy is not well known. The fact that he manufactured and sold instruments for anatomical preparations throughout his career has not been much commented on by historians. The only exception is a suggestion by Morton and Wess of a possible connection between lectures in anatomy and lectures in natural philosophy, based on evidence about a Hauksbee-pump used for bloodletting as well as for demonstrations in pneumatics.[143] In the history of anatomy, only one reference to Hauksbee as a maker of such instruments could be found, but no details were given.[144]

When the combined engine was introduced on the market in November 1701, it was, among other things, described as a syringe useful for injecting air, wax or mercury in anatomy. Later Hauksbee advertised separate siphons for 'injection in anatomy' as well as 'blow-pipes for the same use'.[145] I will here show that Hauksbee's anatomy-siphon was derived from the multi-purpose engine, and that a one-way valve was crucial in this instrument as well as in the blow-pipes. I thus argue that Hauksbee's valve-concept, developed for the cupping utensils and applied in his air-pumps, also became essential for this group of instruments. This underlines the position of the valve as a key component among Hauksbee's contrivances, as well as shedding light on his early career.

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[141] *The Post Man*, 27 Oct (1702). This was the same advertisement where he announced his first separate air-pump and injector.
[142] W. Derham, *Physico-Theology* (London, 1714), 5-8.
[143] Morton and Wess (1993), 55.
[144] G. C. Peachey. *A memoir of William and John Hunter* (Plymouth, Brendon, 1924), 18, 50, 61.
[145] *The Post Man*, 29 Oct (1702).

### 1.3.3.1 Methods and instruments

One method that Hauksbee referred to in his advertisement was the injection of air. Air was injected into body parts by syringes, siphons and blowpipes to inflate them, which were then tied up and dried, a way to preserve their size and form. Another method was to use mercury, for example by injections into the bronchi, blood vessels or lymphatic vessels, which could result in displays resembling silvery trees. The third substance that Hauksbee's engine could handle, wax, was injected while it was hot and soft, and when it cooled, it solidified, keeping the specimen in its original shape (such wax did not escape when the vessels became punctured during handling).[146] Harris's entry on Hauksbee's instruments also describes several other types of fluids. Such injections could be made into parts of the vascular system for displaying the blood supply to various organs, viscera or even whole limbs. The liquids were often coloured, for example vermillion was used in the arteries and various blue dyes in the veins.[147]

The demand for anatomical preparations was rooted in the problem of obtaining bodies for dissection in teaching and research. The number of bodies to dissect was always limited, and they would only last a few days before they deteriorated. Injection-prepared body parts were important pedagogical devices in the anatomy teaching of the period, but the method was also used analytically. By injecting air, mercury and tinged liquor, the early anatomist was able to study how, for example, the arteries and the veins communicated with each other.[148] Together with the microscope, the injector instruments made a considerable contribution to the great progress in anatomy that took place in this period.[149]

Our knowledge of Hauksbee's engagement in anatomy is mainly found in the sales advertisements from 1701 to his death in 1713, and *Lexicon Technicum* (1704). Not much is revealed there, but a close reading of the available material nevertheless makes it possible to 'reconstruct' Hauksbee's anatomical instruments to some extent, an undertaking that makes it clear that there was at least one important difference between his instruments and earlier models. The traditional instruments for making anatomical specimens were syringes, siphons and blowpipes, which all were described and depicted in the literature from about 1670.[150] See Figure 13 and 14.

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[146] K. B. Roberts, *The Fabric of the Body* (Oxford, 1992), 290.

[147] A. M. MacGregor (ed.) *Sir Hans Sloane: collector, scientist, antiquary, founding father of the British Museum* (London, 1994), 295.

[148] There are many examples of this in the contemporary literature, for example by anatomists like James Drake (1667-1707) and William Cowper (1666-1709). It is also possible to talk about a third application, in art, like the preparation of anatomical displays by F. Ruysch (1638-1731), an activity that he was criticized for by contemporaries, for example in the second edition of J. Drake, *Antropologia Nova* (London, 1717). See also: Roberts, (1992), 290-6.

[149] F. J. Cole, 'The history of Anatomical Injections' in *Studies in the History and Method of Science.* ii (2 vols. Oxford, 1921), 285 (footnote); and William Cowper, *The anatomy of humane bodies* (London, 1698) 5.

[150] De Graaf, *De Usu Siphonis in Anatomia* (Leiden, 1688), (an injection syringe); C. Bartholin, *De diaphragmatis structura nova.* (Paris, 1676) (a principle diagram of a siphon for continuous filling),

The anatomy syringe was an ordinary compression syringe with a solid piston, which could be filled with wax or mercury among other materials. Pipes or cannulas of various shapes and lengths could be attached at the lower end and inserted into the vessels. The substance was forced out through the pipes and into the specimens by pressing the syringe-plunger inwards. Air could be injected by simply operating an empty syringe. The combined engine must have worked like this when it was used in anatomy. Another instrument was the siphon, which in fact was a large syringe with an arrangement for continuous filling. The advantage of siphons compared to syringes was that they could supply a continuous flow of injection fluid without redrawing the nozzle from the specimen. This was used when larger volumes had to be injected and the removal of the syringe for recharging was undesirable, since this could cause air bubbles to enter the vessels between the fillings, for example in arteries and veins. A break in the flow of injection material, allowing air to enter, had also to be avoided in those cases where the substance would harden in contact with air. The main component of the siphon, the syringe, was in principle similar to Hauksbee's combined engine. A much simpler device was the blowpipe, an instrument traditionally used in mining and assaying. This was a plain tube that narrowed at one end, channelling air into the anatomical specimens once air was blown into the opposite end.

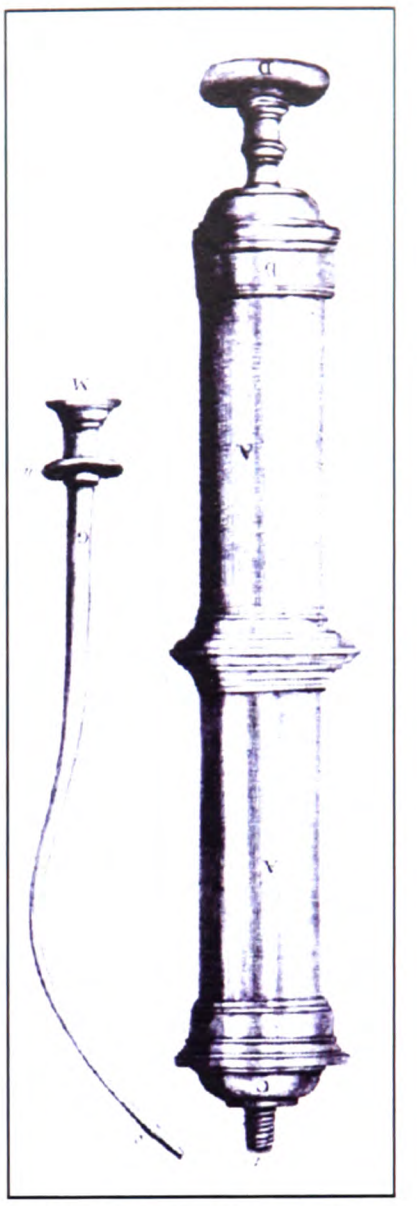


**Figure 13.** De Graaf's injection syringe. A cannula is shown to the left. *De Usu Siphonis* (Leiden, 1688)

### 1.3.3.2 The anatomy-valve

The anatomical instruments illustrated in Figure 13 and 14 were all made twenty to thirty years before Hauksbee got engaged in the trade. His instruments were of the same kind as those depicted, but with one major difference: Hauksbee claimed that his anatomy-instruments possessed 'qualifications beyond any Instrument yet made for that purpose', but did not specify what these new qualities were. When he introduced siphons and blowpipes in October 1702, Hauksbee repeated the claims, but still without an explanation of what was new. However, a small addition, 'with valves', inserted after 'the blowpipe', provides a hint. In later advertisements, the text became standardized to 'Siphons and Blow-pipes with valves for anatomical Injections'.[151] To understand the purpose of these valves, we must turn to the

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and S. Blancard, *Anatomia Reformata*. (Amstelodami, 1688), taf. 51. (a siphon and a blowpipe). A copy of this illustration is also given in Drake (1707).

[151] *The Post Man,* 1 March (1705).

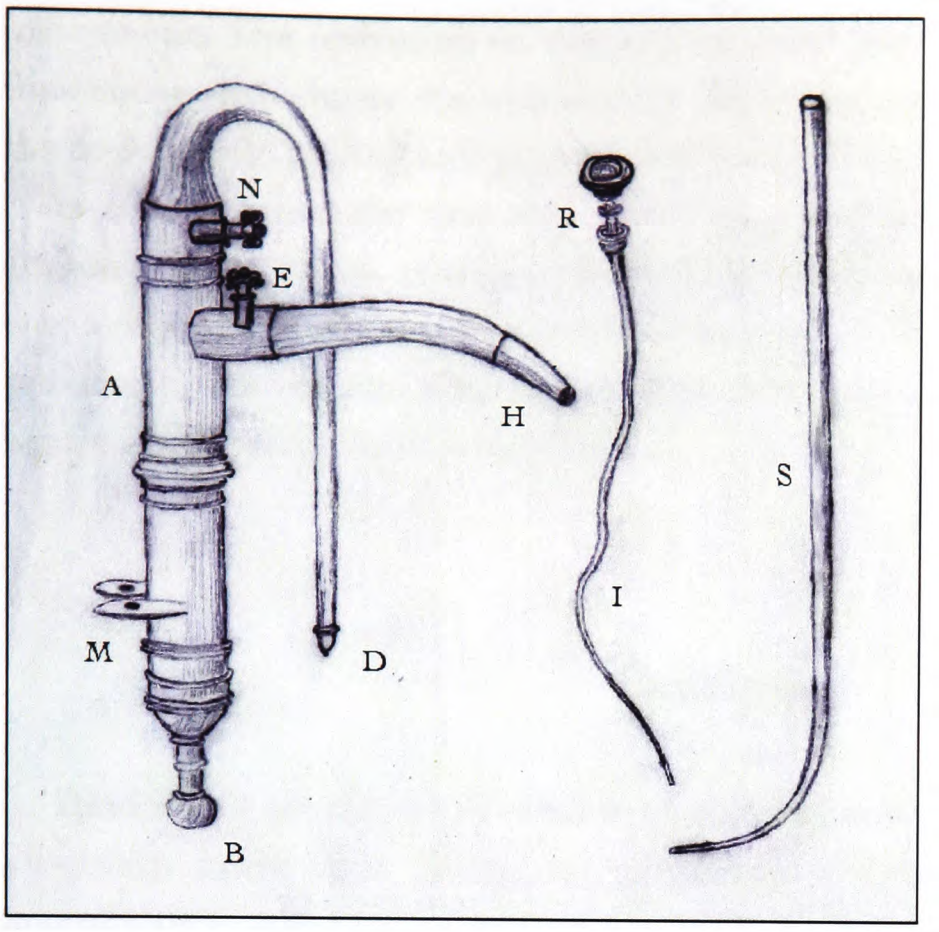



**Figure 14.** Stephen Blancard's injection siphon; attachable pipe (cannula); and blowpipe.

A is the siphon. H is the intake, which is connected to the siphon through a leather hose. D is the outlet at the end of a leather pipe. E and N are the inlet and outlet stopcocks respectively. B is the plunger. M & M are loops for securing the siphon onto a table by nails. I is an attachable pipe (cannula), where the cone R is fastened to the siphon outlet D, by screwing. The long smooth tube H, is a simple blowpipe. The siphon volume was given as 20 ounces of water. (0.6 litre). *Anatomia Reformata.* (Amstelodami, 1688). Redrawn by Terje Brundtland, June 2003.

'Journal Book' of the Royal Society. It is well known that Hauksbee's first performance to the Royal Society on 15 December 1703 was a demonstration of light from mercury in an air-pump, but a fact that has never been commented on by modern historians is that in the next meeting – a week later – Hauksbee let the audience learn about the latest novelties in anatomy and cupping.[152] At this meeting, chaired by Newton, Hauksbee demonstrated the new way of cupping by a small air-pump. He also showed 'a new pipe for blowing with valves so that the air cannot return from that part again', as well as an injecting instrument 'contrived by valves so that the liquor injected into any part cannot return'.[153] What the 'Journal Book' emphasized was that these new contrivances were supplied with valves, so that the air or fluid could not return. The novelty of Hauksbee's anatomical instruments was therefore the addition of automatic valves to prevent backflow of air and fluids from specimens when blowing or injecting had finished.

The advantage of such instruments has been confirmed by Alexander Monro, who later described how blowpipes with valves made the anatomist able to make preparations without support from an assistant.[154] We have no illustration of Hauksbee's blowpipe, but his siphon is shown in *Lexicon Technicum*. See Figure 6, *Y*. In siphons, opening and closing mechanisms are required at both the intake and the outflow to achieve a continuous flow of the injection-fluid, a problem Blancard had solved with two, clearly visible, stopcocks (see above). Nothing like that can be seen on Hauksbee's model, having the one-way valves hidden inside the

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[152] The Royal Society, 'The Journal Book, JBC 10' (London, 1702-1714), 15 Dec. 1703.
[153] Ibid, 22 Dec. 1703.
[154] A. Monro, Secundus, *The Works of Alexander Monro.* (Edinburgh, 1781).

instrument. The operation of this siphon must therefore have been much simpler than those with stopcocks, eliminating the tricky procedure of opening and closing the cocks while pulling and pushing the plunger – in the right order.

It is clear that the one-way valve was a crucial component in Hauksbee's anatomy-instruments as well as in the cupping utensils and air-pumps. The siphon was a more advanced instrument than the multi-purpose engine, where the idea of self-closing valves and absence of stopcocks was transferred from the air-pump, here working with fluids instead of air.

## Conclusion

Hauksbee's air-pumps derived from cupping utensils. I have shown how his first air-pump came into being: it was built through his experience from the manufacture and sale of special cupping glasses and exhausting-syringes, and through the large syringe that also became a model for separate condensing engines and anatomy-injectors.

One aspect of this development is that the air-pump, an instrument originally contrived for scientific endeavours, became applied and refined in popular medicine before it was again turned into a scientific instrument, now much more reliable and user-friendly than its predecessors.

It is also possible to see this development as the start of the instrumental black-boxing process of the air-pump. The most important detail here was Hauksbee's efficient one-way valve. The general importance of this contraption is confirmed in Harris's account of Hauksbee's air-pump, Gray's use of it on his cupping glass, the note about the valve in the 'Journal Book', and Monro's appreciation of blowpipes with valves. An evident correspondence between all these reports underlines the importance of the device. The user of the new air-pump did not need to worry either about leak-tightening or the correct handling of stopcocks, or about uncertainty concerning the vacuum. These elements, which had earlier required a series of technicians, became embedded into the instruments, making the operation much easier and thus diverting some of the attention away from the device itself and more towards its applications.

The next chapter will describe Hauksbee's first air-pump in detail, as well as how he might have been discovered by the learned men of the Royal Society.

# Chapter 2
# Francis Hauksbee's first air-pump

## Introduction

In an unpublished manuscript by Francis Hauksbee on the expansion and compression of air from 1707, there is a sketch of an air-pump and a compressing engine.[155] This image is not found elsewhere in Hauksbee's writings, but the air-pump is of the same kind as the one depicted by Harris, consisting of a single horizontal cylinder, mounted under a pump-plate that is fixed to a table. See Figure 15. Hauksbee's celebrated double-barrelled air-pump was introduced in 1705, a fact that will be thoroughly discussed in Chapter 3. All his experiments prior to this were performed with the single-barrelled model. However, the sketch shows that Hauksbee used this one in his own experiments even after the double-barrelled pump was available, a fact that underlines the importance of the smaller one. The present chapter is a study of this pump and its capabilities, and its role in the 'black-boxing process' of the air-pump – an undertaking that is crucial to our understanding of Hauksbee's role in early eighteenth-century pneumatics.

As demonstrated in the previous chapter, the single-barrelled model was based on cupping utensils. This development can be considered in different stages, where the simple syringe with a 'thumb-hole valve' from January 1699 was the first one. The subsequent models were improved through the addition of automatic valves in the glass and the syringe of January 1701, and the multipurpose engine from November 1701 (when it was being used in the 'air-pump mode'). The next progress was important: a separate air-pump for mounting on a table or in a

[155] The Royal Society, 'The Classified Papers', Cl.P (London, 1703-15), 110. Undated draft. Inserted between sheets dated 20 March and 7 May 1707. Papers that are dated are arranged chronologically in this volume.

windowsill, first advertised in October 1702. This was the version that Harris described, and the one that Hauksbee used for his own experiments in 1707. By searching for the roots of Hauksbee's double-barrelled pump, however, it became evident that he had made yet another version of the single-barrelled type. A short survey of this version is necessary since it represents the final link to the double-barrelled model.




**Figure 15.** Francis Hauksbee's single-barrelled air-pump. Unpublished manuscript. Hauksbee's signature to the right. Compare with Figure 6. The Royal Society, Cl.P (1707), 110.

## 2.1 Towards the single-barrelled pump

### 2.1.1 The fifth stage

A close study of Hauksbee's first articles in the *Philosophical Transactions* makes yet another stage of this air-pump apparent. The pump depicted by Harris, and also in the unpublished manuscript, was like an assembly of different parts: the receiver, the barrel and the barometer. These were fastened to a receiver-plate, which was fixed by screws to a table.[156] In contrast, the classic Hauksbee-pump was a separate, self-standing construction with four legs, holding the pump-barrels and the barometer. (Figure 5). I will in the following show that Hauksbee made a separate, self-supporting pump-stand for his single-barrelled air-pump as well, a contrivance that can be described as a fifth stage in the development of his early air-pump.

In the *Philosophical Transactions* of December 1705, Hauksbee described a large experimental set-up for some trials on the attrition of different bodies in vacuum. This was accompanied by an illustration depicting a large wheel-arrangement on top of a ladder and a pump-stand with a receiver, connected in a way that made the operator able to rotate various objects inside it.[157] See Figure 16a. This article is also reprinted in Hauksbee's book of 1709 with minor corrections, but the illustration there is replaced with one containing the more sophisticated double-barrelled air-pump (16b).[158] The fact that Hauksbee's book is mostly a collection of previous published, and more or less edited, articles, is well known,[159] but that the two actual illustrations are different has received less notice. There is no reference to this image in current historical literature; all modern authors who have discussed and supplied a figure of the attrition (chafing) experiment have used the 1709 version.[160] Compare the two images in Figure 16: the stand in Figure 16a holds neither a pump-barrel nor a barometer, but since it is described as a pump in the text, these components must have been left out for the sake of simplicity.

The text does not mention the number of cylinders explicitly, but it is obvious that the image depicts a self-supporting stand for the single-barrelled-pump and not one for the double-barrelled version. First, the stand itself is not the same as the one that holds the different components of the double-barrelled pump together. It is of a simpler construction. All the four legs go straight from the receiver-plate to the floor, and the lower plate that was used to support the two brass barrels on the

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[156] Harris (1704), Plate with air-pumps.

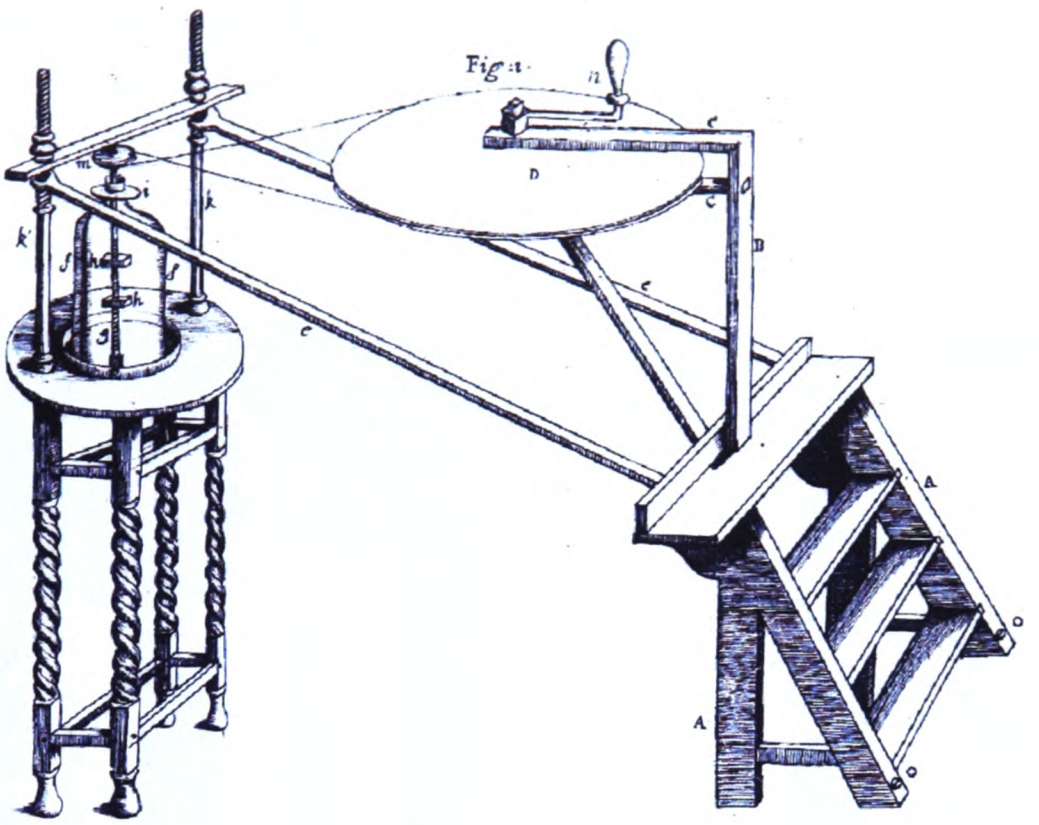
[157] F. Hauksbee, 'Several Experiments on the Attrition of Bodies in Vacuo', *PT* vol. 24 (1705), 2165-75; Tab 2.

[158] *PME*, 21; Plate II.

[159] D. H. D. Roller, 'Introduction' to Physico-Mechanical Experiments', *The sources of Science* (H. Woolf, ed), no. 90 (London, 1970), xvii.

[160] Roller (1957), ii, 562; J. Heilbron, (1979), 231.

16a




16b

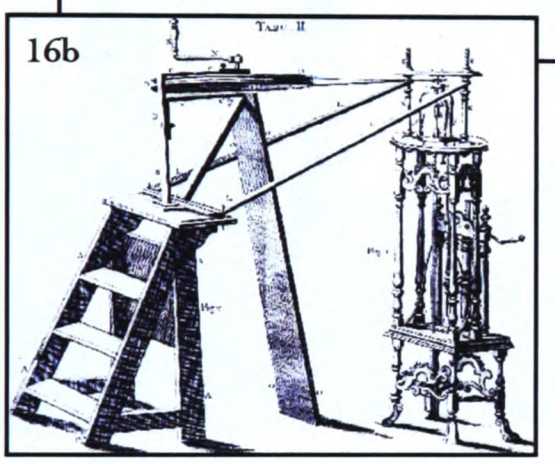


**Figure 16 a** (above). The fifth stage in the development of the single-barrelled air-pump, here applied in the chafing experiment. *PT,* Dec 1705.

**Figure 16 b** (left). The common illustration of the same experiment, shown with the double-barrelled pump. *PME* (1719), Plate II.

classic pump is absent.[161] Second, from a close reading of Hauksbee's articles in the *Philosophical Transactions* prior to the contrivance of double-barrelled air-pumps, another argument for a separate, freestanding single-barrelled air-pump emerges. Hauksbee wrote that he shook the pump at several occasions to 'trigger' some experiments, for example in one regarding production of light from a mixture of Phosphorus and 'Oyl of Vitriol' kept in a dish inside an evacuated receiver. In another he studied sound from a bell in vacuum. In the former he shook the pump in order to set the liquid in the dish in motion and see whether it emitted light, in the latter for making the clapper strike, and it becomes clear that this was a normal and natural procedure in such experiments. What is obvious here is that Hauksbee must have been able to move, or shake the whole pump. Even if he said he was 'shaking the receiver', it must mean the entire construction, since the receiver itself was clamped to the pump-plate by the external air-pressure. The single-barrelled air-pumps that was depicted by Harris could not be easily shaken like this, however, as the pump-plate was secured to a table or a window frame, which made

[161] The style is different from the double-barrelled model as well, as this one has twisted legs.

shaking or moving the receiver difficult or impossible. It is therefore apparent that under these circumstances, Hauksbee must have performed the experiments in a receiver that sat upon a freestanding pump with a single barrel and an attached barometer. This must have been the fifth and the last step of development before Hauksbee was to make the classic double-barrelled pump. A diagram showing the five stages is given in Figure 17.

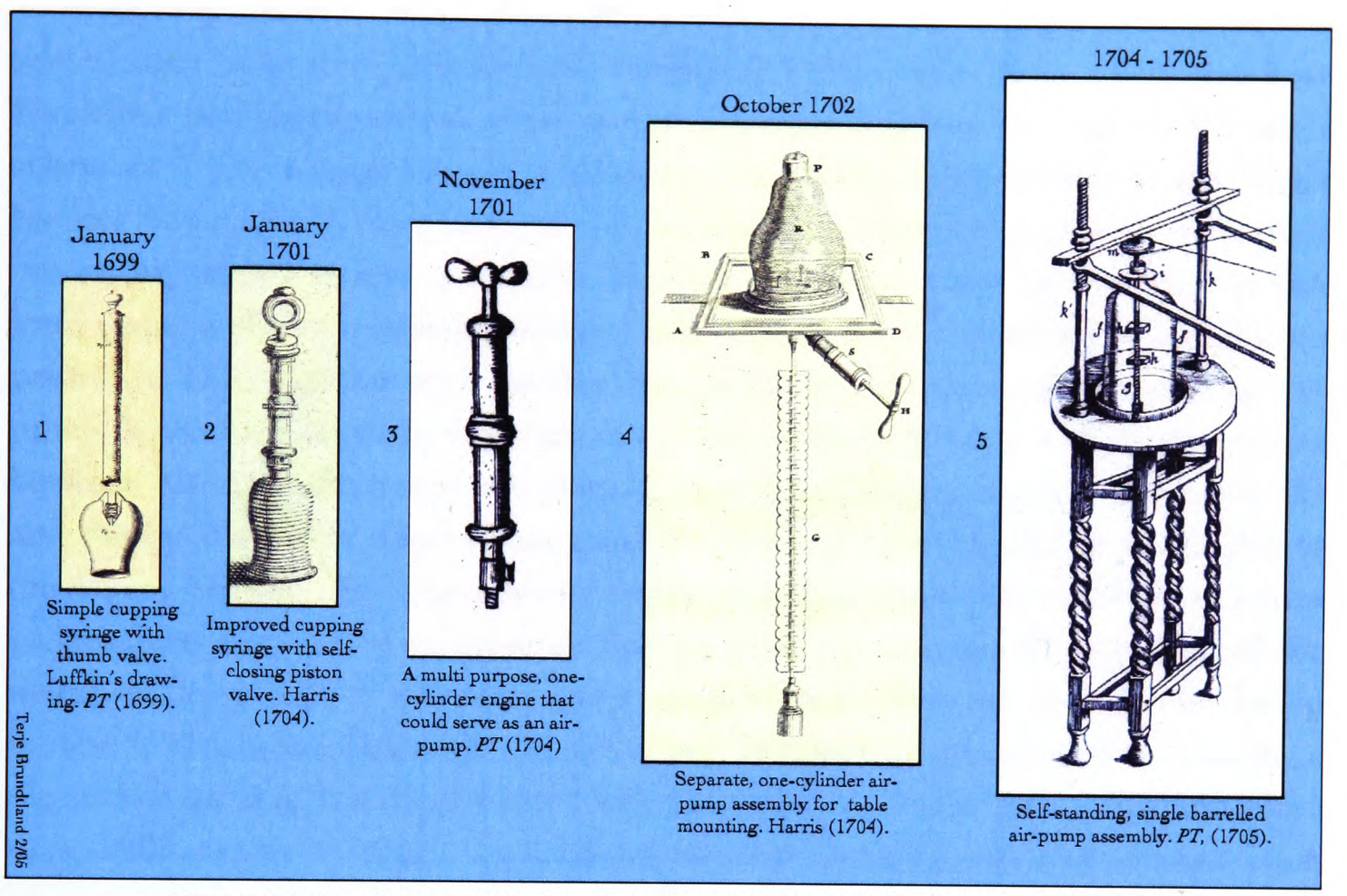



**Figure 17.** Hauksbee's five stages of the single-barrelled air-pump. 1699-1705.

### 2.1.2 Hauksbee and the Royal Society

Hauksbee's double-barrelled pump was introduced in May 1705. The pump that he presented to The Royal Society on 15 December 1703 could therefore *not* have been this model, something that has been taken for granted by every modern historian until now.[162] The note in the 'Journal Book' described the device as 'a new invented air-pump', and it could have been either the table model of 1702 or the freestanding version described above.[163] One possibility is that it was the table model (stage 4) that he first brought to the Society, and inspired by the interest and appraisal shown by the philosophers there, he continued its development into the self-supporting model. It could also have been furthered by demand from the market. But the most important issue here is not the question of whether it was a table-model or a freestanding version he presented to the Royal Society, but all the

[162] See the Introduction, page 31.
[163] The Royal Society, 'The Journal Book', JBC 10 (London, 1702-1714), 15 Dec. 1703.

features that this pump possessed. These qualities are reflected in some contemporary assessments of Hauksbee's pump, all given in 1704. Harris described Hauksbee's air-pumps as 'the best that he ever had seen', and William Derham underlined both the easy pumping and barometer control.[164] James Hodgson, with whom Hauksbee cooperated in giving public lectures, described his pump as 'improved'.[165]

Regarding issues on Hauksbee's first performance in the Royal Society and how the contact was first established, Heilbron writes that 'it is unknown how Hauksbee had prepared himself as an experimenter and how he came to Newton's attention.[166] The engagement of Hauksbee as a weekly demonstrator in the Royal Society has normally been seen in connection with Newton's initiative to restore the society after a period of decline. Hauksbee's introductory performance in fact took place at the first meeting where Newton was in charge as the newly elected president. This, together with the fact that Hauksbee's demonstration was of an air-pump, have made modern commentators look exclusively for possible connections between him and other experimenters in natural philosophy, such as Boyle, Hooke and Papin. We might never know exactly when and how, Hauksbee was called to the Royal Society. His engagement might well have been part of Newton's new programme, but I see it as apparent that he must have caught the attention of the members long before his entry, and then without Newton necessarily being involved. Hauksbee was a fervent advertiser of cupping-utensils and air-pumps in the newspapers in London before December 1703, and after going through more than 1000 copies of them, I can claim he was the only one that offered such commodities to the public. During certain periods Hauksbee advertised rather regularly, and it must in practice have been impossible for the Fellows of the Royal Society, who presumably read the papers, not to have learned about him or his products. In one advert Hauksbee claimed that his cupping utensils were well-known and appreciated by physicians and surgeons,[167] and in May 1699 he stated that his method was 'practiced by several eminent Surgeons of this City'.[168] He must also have been known outside London, since he offered his products by mail order to people living in the 'Country'.[169]

From the new evidence concerning Hauksbee's production of cupping and anatomical instruments that I presented in the previous chapter, and the fact that several of the members of the Royal Society were apothecaries, physicians and surgeons, I find it likely that some of these were among the consumers of his devices.[170] Consequently, the first contacts could have been made early, even before

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[164] W. Derham, 'Experiments about the Motion of Pendulums in Vacuo', *PT*, vol. 24 (1704), 1785.
[165] *The Daily Courant*, 9 Dec (1704).
[166] H. Guerlac (1989), 169; Heilbron, (1979), 229.
[167] *The Post Man*, 31 Jan (1699).
[168] *The Flying Post*, 9 May (1699).
[169] *The Post Man*, 16 Aug (1701).
[170] In the period 1690-1700, about 20% of the elected members belonged to this group. See: M.

air-pumps became standard commodities. One possible candidate for such an encounter would be the surgeon, anatomist and writer William Cowper who, for example, used anatomical injectors.[171] A meeting between Hauksbee and a member of the Society definitely took place the end of 1702, when John Harris visited Hauksbee's shop and saw a large 'acute' barometer.[172] It was also in this period that Harris announced subscriptions for his work, the *Lexicon Technicum*, then in preparation.[173] When it was published in 1704, Hauksbee's name was on its list of subscribers.[174]

Hauksbee must have been a public figure in London during this period, and we can no longer say that he 'emerged from obscurity' like Henry Guerlac has assumed. Similar to questions surrounding the versions of his first pump, the most important issue is not how he became known and when he first got in contact with the Royal Society. What counts more is that Hauksbee, in this early period, must have achieved competence, experience and reputation as an outstanding instrument-maker, which proved to be extremely fruitful in his further activities in experimental philosophy.

Based on the belief that the appraisals of Harris, Derham and Hodgson reflect judgements of the double-barrelled pump, and given the lack of information on Hauksbee's activities prior to December 1703, modern commentators have until now had problems explaining the qualities and the sudden appearance of this particular air-pump. Misconceptions about Hauksbee's air-pumps and speculations about his background have contributed to the modern Hauksbee myth. Assessing the qualities of the single-barrelled pump – to which the contemporary appraisals were directed – will therefore be helpful and necessary in our way towards a more complete understanding of Hauksbee and his air-pumps.

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Hunter, *The Royal Society and its Fellows, 1660-1700* (Oxford, 1994).

[171] W. Cowper, *The Anatomy of the Human Body* (Oxford, 1698).

[172] Harris (1704), under 'Barometers'. Hauksbee invited people to come to his shop and see this barometer in October 1702. This was in the same advert where he announced the single-barrelled pump for the first time
See: *The Post Man*, 27 Oct (1702).

[173] An advertisement for *Lexicon Technicum*, with an apology for delayed publication and a final invitation for subscribers was announced in *The Post Man*, 9 Oct (1703).

[174] Harris (1704), under 'Subscriptions'.

## 2.2 Why it was better

### 2.2.1 Boyle, Hooke and Papin

When Hauksbee first advertised the engine that could serve as an air-pump in November 1701, he characterized it as a contrivance that could perform experiments in vacuum 'with ease and exactness, and without the use of cement and stopcocks'. This portrayal was used for the separate air-pump in every advertisement from 1701 to 1703. I have in the previous chapter used the terms 'ease' and 'exactness' when I showed that the first pump was derived from cupping utensils. Here I will use the same terms to discuss this pump in depth.

It is interesting to observe that both Hauksbee and, as I will show, Harris, emphasised the lack of cement and stopcocks. These issues were characteristic of Boyle and Hooke's first and second air-pumps from the period 1659-70, but not of Papin's double-barrelled pump with self-closing valves from 1678. A short survey of this pump is therefore necessary for understanding the state of pneumatics in England at the time of Hauksbee's first air-pump. Papin's pump is also called Boyle's third, and was described in his book, *A Continuation of New Experiments (...) The Second Part,* of 1682.[175] I will argue, based on relevant seventeenth- and eighteenth-century sources, that this pump was not as important as modern authors believe it to be. For example, neither the book nor the pump is referred to in any articles in the *Philosophical Transactions* in this period.[176] John Houghton (1645-1705) attributed the invention of the air-pump to the 'Honourable Boyle' in his weekly paper *A Collection for the Improvements of Husbandry and Trade* from June 1692, when he discussed air-pumps and air-pump experiments in the Royal Society. Papin's double-barrelled pump was not mentioned at all. Houghton used the expression 'when the Exhauster has drawn out the air' in a description of an experiment, which sounds like the operation of a single-barrelled pump.[177]

A corresponding study of texts on air-pumps following the Hauksbee-period yields even less about Papin. His double-barrelled pump was not mentioned in Wimmerstedt's dissertation on the history of air-pumps from 1734,[178] or in the 1736 edition of Harris's *Lexicon Technicum*. Nor was it referred to in Desaguliers's comprehensive texts on experimental philosophy from 1734 and 1744.[179] Samuel Johnson did not mention it in his *Dictionary* of 1755, but said that Hauksbee removed the laborious pumping of the early air-pumps by introducing a second

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[175] *Boyle's Works*, ix, 123-263.

[176] A *Continuation of New Experiment (...), The Second Part,* was reviewed in the rather obscure *Weekly Memorials for the Ingenious* (London, 11 Dec, 1682), 335-9, where the pump is only mentioned briefly.

[177] J. Houghton, *A Collection for the Improvements of Husbandry and Trade,* vol. 1, no. 17, 4 June (London, 1692).

[178] J. Wimmersted, 'Geschichte Der Luftpumpe', *Wissenchaftliche Zeitchrift.* vol. 33, part 2 (Magdeburg, 1989), 116-126. First published in 1734.

[179] Desaguliers (1734, 1744).

barrel.[180] Both Croker's *The Complete Dictionary of Arts and Science* from 1764, and a similar work by Middleton from 1778, emphasised Boyle and Hooke's pumps, as well as Hauksbee's double-barrelled one. Papin was not discussed at all.[181] The only contemporary text (beside Harris, 1704) I could find that mentioned Papin's pump was Roger Cotes's *Hydrostatical and pneumatical lectures.* Written between 1713 and 1716, Cotes (1682-1716) claimed that Hauksbee's double-barrelled pump was better 'in all respects'.[182]

Papin's absence from these texts suggests that the double-barrelled pump had fallen more or less into oblivion, even before Hauksbee entered the scene in 1699. They show that Boyle's first two air-pumps had left a stronger impressions on English philosophers than Papin's air-pump had done. A good illustration of this is found in Harris (1704), where, after an extensive account of Boyle and Hooke's pumps, he reprinted the description of Papin's pump from the *Second Continuation* before claiming that:

> The Ingenious Mr. *Hawksbee* now makes *Air-Pumps* of a much simpler and easier Form than these Engines above described, and in which are many Conveniences which they had not.

Harris then went on to describe Hauksbee's single-barrelled pump, using elements from Boyle's first pumps as background. It is clear that for Harris, Papin's double-barrelled pump had not achieved the same status as Boyle's pumps, despite being presumably quicker and easier to operate.[183] It had definitely not become the definitive air-pump of the seventeenth-century.[184] The idea 'Air-Pump' must still have meant Boyle and Hooke's single-barrelled models to most people, and was therefore the natural backdrop for a review of Hauksbee's model.

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[180] S. Johnson, *Dictionary of the English Language* (London, 1755).

[181] T. Croker, *The Complete Dictionary of Arts and Science* (London, 1764); E. Middleton, *The new Complete Dictionary of Arts and Science*, (London, 1778).

[182] R. Cotes, *Hydrostatical and pneumatical lectures* (Cambridge, 1747).

[183] The *Second Continuation* described it like this: 'a man may easily judge, that that the two Pumps of this engine may be plyed with greater ease and more speed, then one Pump in a single engine can, so that this engine is of great use in order to those Experiments, which cannot be very well made, but with velocity and speed'. See *Boyle's Works*, ix, 136.

[184] It is possible to question the general efficiency of Papin's double-barrelled pump. When Papin's built his next air-pump about 7 years later, he had abandoned the idea of the two cylinders, and partly that of the self-closing valves, since the new pump had one vertical barrel, and one water-covered and one manual operated valve (Figure 25).This evidence reduces the modern assumption of the importance of Papin's double-barrelled pump even further. See: D. Papin, *A continuation of the new Digester of Bones* (London, 1687), 44-7.

## 2.2.2 Ease

### 2.2.2.1. Pumping without stopcocks

A major concern for seventeenth-century natural philosophers working with air-pumps was the difficult and time-consuming effort of emptying the receiver of air. In other words, the pumping action itself. This included both continuous operations of the plunger as well as controlling the directions of the airflow with stopcocks. A study of this procedure, especially with Boyle's two first air-pumps, reveals that pumping was a complicated and physically arduous task. Consequently, a survey of such operations is necessary to see the full advantage of Hauksbee's pumping method.

To start evacuation with Boyle's first air-pump, the stopcock that connected the pump-cylinder to the spherical receiver had first to be closed and a brass peg put in place in a hole in the upper part of the cylinder-wall. See Figure 6; *Fig. I, S* and *R*.[185] Pumping began by driving the plunger downwards with the crank. When the plunger had reached the lower position and the pressure in the barrel had been reduced, the connecting stopcock was opened so that the air could flow from the receiver into the barrel.[186] The receiver, now containing a partial vacuum, then had to be closed off by turning the stopcock before the barrel was opened to the atmosphere by removing the stopper (the brass peg). The stopper had to be put back when the piston had been cranked to its innermost position again, and a new cycle could begin.

This was a complex operation, which normally required several people. When the piston had been driven to its outmost position with the stopper in place and the stopcock closed, the external air pressure would try to force it inwards again. The operator could only prevent this by withholding the crank from rotating. The crank had to be withheld until the stopcock had been opened and then closed (to let air from the receiver into the barrel), and the peg being removed. A rough estimate suggests that the force needed to turn and withhold the crank was approximately 10 kg. This procedure also required the turning of the stopcock and the removal and replacing of the stopper to be done in the right order, as well as the fact that it had to be synchronised with the movements of the plunger. A similar course of actions was required with Boyle's second pump. A mistake here would result in the receiver being filled with water. See Figure 18.[187]

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[185] *Boyle's Works*, i, 163.

[186] Guericke, for example, had placed the receiver on top of the barrel 'so that the air would drop out of it by its own weight'. Boyle used the expression 'the air would nimbly descend into the Cylinder' about his first pump (1659). On his second pump, however (1662), he wrote that 'the Air will (...) pass freely by virtue of its own spring out of the Receiver and into the exhausted Cylinder'. See *Boyle's Works*, i, 163: and vi, 38. See also Helden (1991), 157, about the concept of 'air dropping out of the receivers'.

[187] *Boyle's Works* vi, 37.

Other air-pumps makers had eliminated the stopper by using two stopcocks, or simplified the operation further by applying a single three-way cock. Denis Papin, for example, had used such a stopcock on a single-barrelled pump in 1674 while working in Paris. He had also supplied the piston rod with a stirrup, leaving the hands free to operate the valve, and thus made the pumping into a one-man task. In Holland, Wolfred Senguerd had made a large, inclined, one cylinder-pump with rack and pinion drive in 1679, which also incorporated a three-way cock in reach of the operator.[188] However, pumping still consisted of two elements: the pulling of the piston and the opening and closing of the valves. The use of stopcocks was clearly a characteristic and cumbersome element of seventeenth-century air-pump practice.

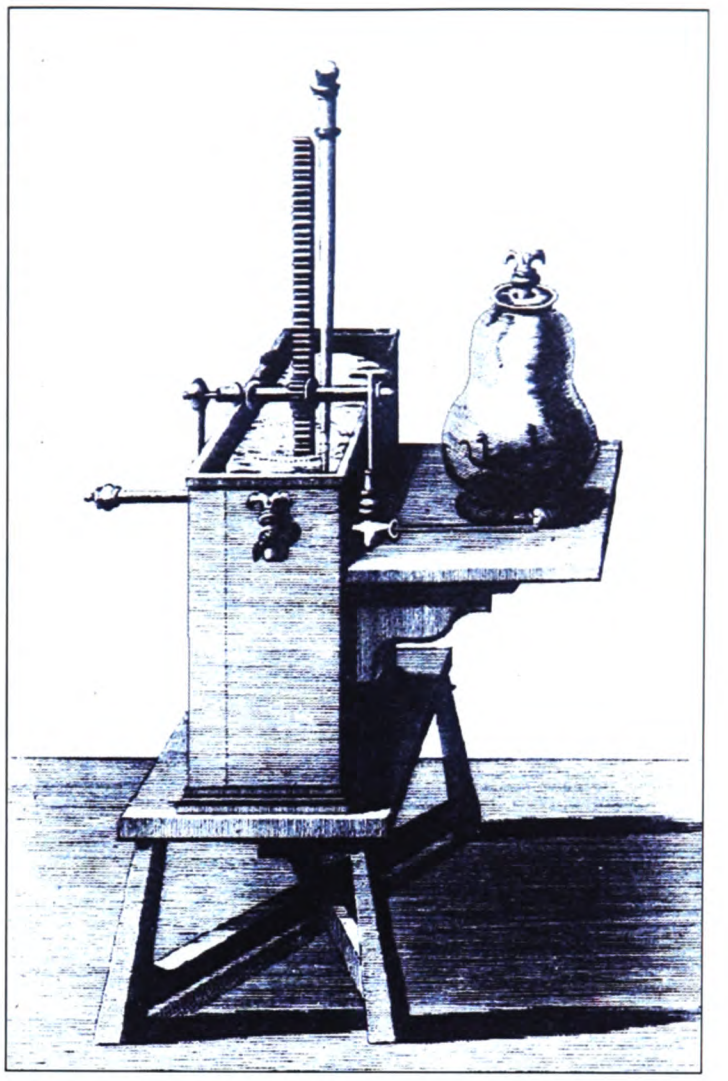


**Figure 18.** Boyle/Hooke's second air-pump, 1662. The barrel was immersed in water in the tank at left. The tall stick (with the same function as the brass-peg on the first pump) had to be removed and put back at the right instant during the pumping cycle. If not, the receiver would be flooded with water. *Boyle's Work*, vi, 26.

The survey above shows that Hauksbee's repeated stress on the lack of such devices in the advertisements was more than just a sales promotion. Instead it signified a crucial feature of his pump – simplicity. According to Harris, it was the function of Hauksbee's automatic valves that caused the easy operation of the pump:

> ...which means the Recipient is very easily exhausted, the Valves much better supplying the use of Stopcock in other Engines of this nature.[189]

While a characteristic feature of Hauksbee's air-pump was the absence of stopcocks, the secret behind it was, as we can see, the valves. The development and operation of these valves are described in detail in the previous chapter, and here their importance becomes confirmed by Harris. The fact that Hauksbee emphasised the lack of stopcocks instead of the advantages of the valves for attracting attention from the newspaper-readers is understandable. To open and

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[188] Helden (1991), 163-64.
[189] Harris (1704), under 'Air-pumps'.

close the stopcocks manually while pushing the plunger in and out were characteristic and familiar elements in the operation of Boyle's air-pumps. With such pumps, one pumping cycle would have required at least six operations with the stopcock and the stopper (three with a three-way cock) in addition to the pulling and pushing of the plunger. With Hauksbee's first model, it was just to pull out and push in the plunger, and the automatic valves in the elbow beneath the pump plate and in the piston did the rest, keeping the achieved vacuum inside the receiver.[190]

Hauksbee's system made the whole enterprise of experimenting with the air-pump a one-man task. It also reduced the pumping time considerably, since no halts between the plunger strokes were required to operate the stopcocks. This reduction in the need for human labour and time must therefore clearly be one of the 'many Conveniences' that Harris and other contemporaries referred to.

#### 2.2.2.2 Sealing techniques

Another significant issue concerning pre-1700 air-pump technology was the problem of leaks. This had been a major concern for Boyle and Hooke, as well as for Huygens and Papin. Typical of Boyle's first pumps was the extensive use of sealing wax and cement to avoid leaks, especially between the glass-receiver and the pump-structure. Huygens and Papin had developed leather-seals with some success, and it was probably this method that was used on Papin's double-barrelled air-pump. However, like the stopcock-versus-valve issue, both Hauksbee and Harris used characteristics of Boyle's two first pumps to demonstrate the advantages of Hauksbee's sealing methods. While it could be argued that this is simply to make the comparison more flattering to Hauksbee, it might also be taken as yet another indication of the less significant role of Papin's double-barrelled pump. Therefore, to understand the contemporary impact of Hauksbee's first pump with regard to sealing techniques, we have to compare it with Boyle's first and second models.

Leak-tightening was not only a practical problem. Shapin and Schaffer have shown that leaks, and attempts to avoid them, were important issues related to the acceptance of the air-pumps as an instrument that could produce matter of facts about nature, something that becomes clear from the debate between Boyle and Hobbes.[191] On Boyle's first pump, the spherical receiver was fastened and sealed into the pump-structure by a mixture of hot pitch, rosin and wood-ashes (Figure 6; *Fig. I,* at *T* and *V*).[192] His second pump was of a different construction with a bell-

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[190] It is also possible that Hauksbee generally regarded his cupping and air-pump valves as trade secrets, and was reluctant to reveal more than necessary to the public. Another possibility is simply that they were left out to reduce the advertisement-costs.

[191] Shapin and Schaffer (1985), 116-7. See also Helden (1991), 162.

[192] *Boyle's Works,* i, 161. This cement was traditionally used by glass-grinders to glue pieces of glass, too small and fragile to be hold by ordinary tools, onto special sticks. After grinding, the object could easily be loosened by warming the cement. See *Boyle's Works*, vi, 495-6.

shaped receiver placed on a horizontal base-plate with a hole for pumping (Figure 18). This concept had many advantages, but leakage along the receiver-rim was always a problem. Boyle solved it by fixing the receiver to the base by sealing wax. The importance of this issue is illustrated by the fact that Boyle and Huygens had discussed the matter, and Huygens had come up with a special recipe for cement, which Boyle later adopted. A mixture of equal parts of Bees-wax and Turpentine was the best, according to Huygens, as it would stay soft for months, and not stick to the hands.[193] For the cement to be useful throughout the year, Boyle had to use different proportions of the ingredients in summer and winter.[194] A thick paste can be seen outside the rim on many of Boyle's receivers, showing that the required amount to seal it off was considerable. See Figure 19 and 20.[195] The cement was applied with a hot iron and it must have been very time-consuming first to heat it, then apply short parts of the cement onto the receiver-rim before it cooled; then heat the iron again and apply a new portion of cement. The diagonal structures that are visible in the cement around Boyle's receiver-rims must have been an attempt to illustrate the result of this operation.

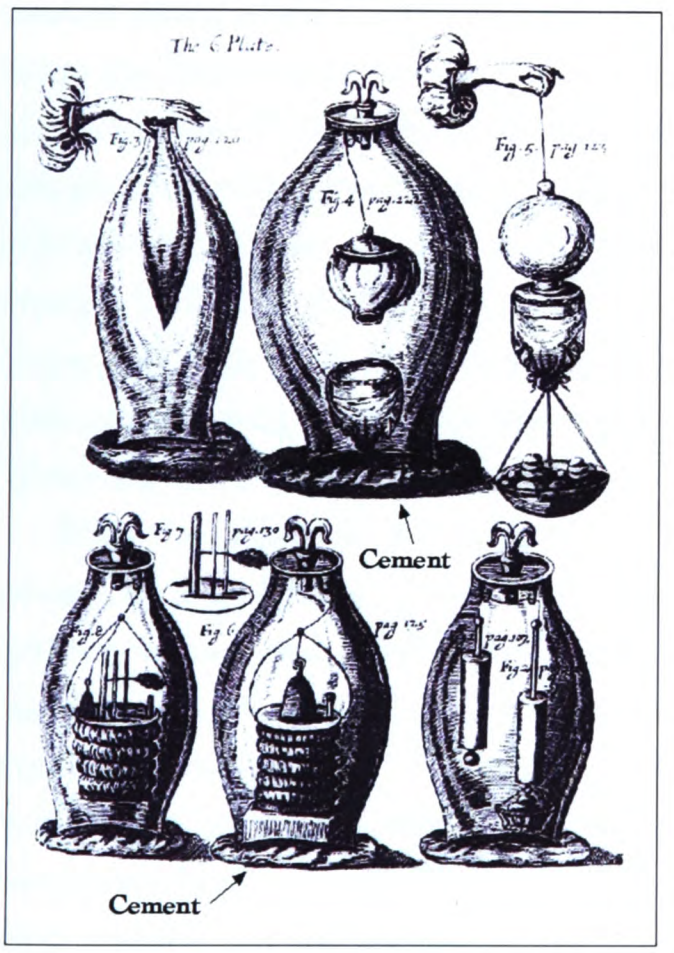



**Figure 19.** Cement outside Boyle's receiver rims for making them leak-tight. The three upper arrangements involve cupping glasses. *Boyle's Works*, vi, 115.

It is evident from Boyle's account that the preparation of an experiment, including arranging the apparatus for vacuum-tests on the pump plate was one issue, while sealing the receiver to the plate with sealing wax was another. We can, for example, find the note: 'when the receiver had been cemented to the pump plate' between Boyle's description of the apparatus, and the description of the experiment itself.[196] He also reported that heat from the cement and the applying iron might cause air inside a barometer in the receiver to expand.[197] Therefore one reason why Hauksbee's pumps were seen as better than previous models was that he had eliminated the use of cement, which included issues like handling, mixing and preparation, as well as the tedious application process. To break up and remove the cement after an experiment was over must also have been time consuming,

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[193] Stroup (1981), 131, 152.
[194] *Boyle's Works*, vi, 38. Also described by Harris (1704), under 'Air-pumps'.
[195] Ibid, 115, 133, 141.
[196] Ibid, 143.
[197] Ibid, 44.

and include the chance of breaking the glass-receiver.

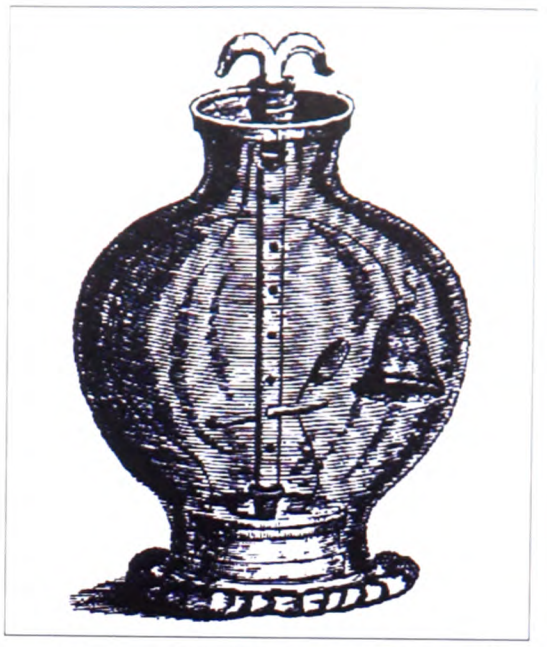


**Figure 20.** Wide receiver with a narrow opening (mouth) at the base. From Boyle's sound-experiment. *Boyle's Works*, vi, 141.

I have shown in the previous chapter that Hauksbee emphasised the lack of cement in his advertisements, and that he was instead able to make reliable seals from leather – a feature clearly transferred from his cupping utensils. However, Huygens and Papin had earlier used leather for air-pump seals, and we cannot exclude the possibility that Hauksbee knew about this. However, a survey of their efforts shows that such sealing-methods were not without obstacles, and this in turn illustrates the quality of Hauksbee's improvements. Huygens had tried to use leather-gaskets between the receiver rim and the base-plate, but found it not fully satisfactorily. He had tried different kinds of leather, like eel, mutton and lambskin. Eel skin was least useful, since it grew springy as it dried, and this spring raised the receiver a little from the base-plate, creating gaps at some places along the receiver rim, which caused leaks. Wetted mutton-skin was not good either since it was porous. Water droplets would form on the leather inside the glass bell during evacuation, and when it had dried up, the seal started to leak. Huygens had more success with wetted lambskin. On one occasion he managed to keep a receiver sealed for several days, and with some turpentine around the rim, he could even extend this period.[198] But since using leather-gaskets does not seem to be straightforward, why did Hauksbee succeed?

First, he must have been able to pick the right sort of leather and prepare it properly. He did not mention this in particular but did describe how thick and porous leather did swell in a vacuum.[199] Second, Harris emphasised that Hauksbee used a thin piece of wet leather between the receiver and the base-plate, which required a smooth and flat pump-plate as well as receiver rim. This was a necessary feature for obtaining sufficient leak tightening, and Hauksbee described on a few occasions how he had the receivers ground to obtain a flat surface.[200] A third issue that clearly had influence on leaks was the receiver-size. From one point of view, small receivers were preferable since the shorter circumference of the rim gave fewer opportunities for leaks.[201] If large receivers were required because of the size of the apparatus inside, Boyle preferred special shaped receivers, narrowing in

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[198] C. Huygens and D. Papin, 'Some Experiments Touching Animals', *PT*, vol. 10 (London, 1675), 544.

[199] F. Hauksbee, 'Experiments on the Resilition of Bodies', *PT*, vol. 24 (1705), 1947.

[200] F. Hauksbee, 'Several Experiments on the Attrition of Bodies in Vacuo', *PT*, vol. 24 (1705), 2165; *PME*, 3.

[201] *Boyle's Works*, vi, 38.

towards the base.[202] While they had a volume sufficient for experiments, the smaller mouth would reduce the problems with leaks. See Figure 20. On the other hand, the pressure that a rim exerts on a gasket increases in proportion to the diameter of the opening (if the thickness of the rim is kept constant). The larger the opening is, the more the rim became forced into the leather. This effect in turn increases the chances for sufficient leak-tightening as the gasket becomes more compressed (it is unknown if Hauksbee was aware of this).

The reason that, for example, Huygens did not succeed with porous eel-skin could have been that his receivers were too small and consequently the external air pressure insufficient to press the glass into the swollen skin and close its pores, and as such make a leak-proof joint. One element in Hauksbee's success seems therefore to have been the size of his receivers. The lower openings of the receivers depicted by Harris are less reduced compared with those of Robert Boyle (Figure 6; *R* and *R.2*). This is even more evident with Hauksbee's chafing experiment, published in 1705, where the depicted receiver had a cylindrical shape, allowing full access to the receiver space (Figure 16). Finally, it is clear that the leather-seal had to be kept wet to provide sufficient tightening. To prevent it from drying up, the receiver was placed on a brass plate in a hollow on the pump-plate, which contained water. See Figure 21. Though water is not mentioned explicitly concerning the single-barrelled pump, the hollow is, and it is visible on the illustration (Figure 6). Water for sealing purposes is, however, described in Hauksbee's account of the double-barrelled pump (1709), which had a similar receiver-arrangement.[203]

Hauksbee's success was therefore a combination of at least four elements; the right sort of leather for the gaskets, flat receiver rims, sufficient receiver size, and a designated water-reservoir for keeping the leather moist. This facilitated 'cement-free' air-pumps, which gave a series of advantages. First mixing, handling and application of sealing-wax became unnecessary; second, time for preparing a 'pump-down' was reduced or eliminated; and third, receivers with full openings could be applied. These characteristics must clearly have made Hauksbee's air-pump better than earlier models.

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[202] *Boyle's Works*, vi, 115, 141.
[203] *PME*, 3.

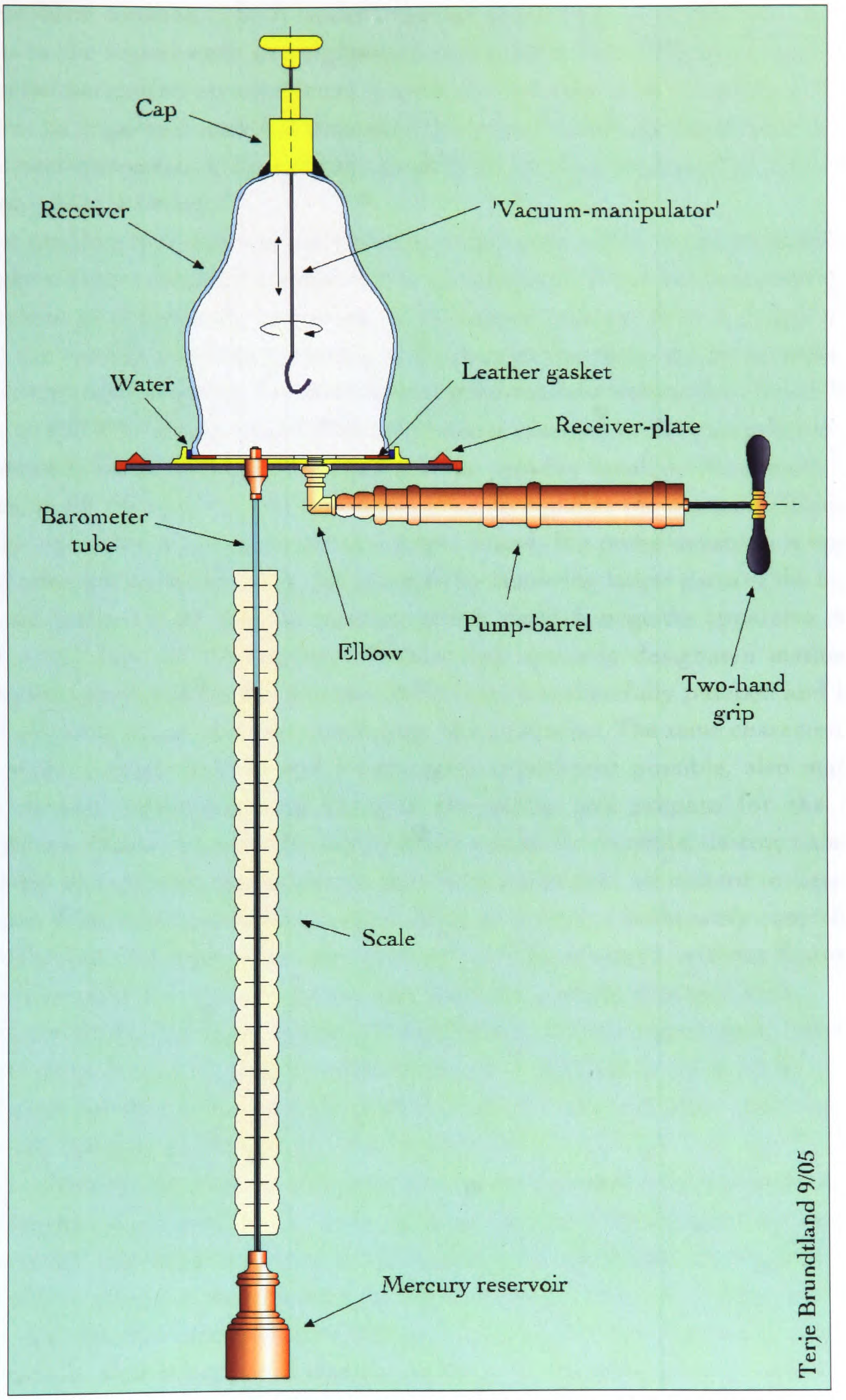



**Figure 21.** Francis Hauksbee's single-barrelled air-pump. October 1702. See also Figure 11 and 23.

### 2.2.2.3 The vent valve function

A problem common to both modern vacuum-technicians and those who used air-pumps in the seventeenth and eighteenth centuries is the difficulty of opening an evacuated pump after an experiment is over. According to early air-pump accounts, this was an important issue but it seems to have been totally overlooked by modern instrument-historians. It has not been possible to find any discussion of the topic in the secondary literature.

The problem is an effect of the ambient air-pressure, which exerts a considerable pressure on the evacuated components of an air-pump. It can be illustrated by the difficulties of deliberately removing an evacuated receiver from a pump board, when the outside pressure is forcing it down onto the plate. As an example, the ambient pressure working downwards on a glass-receiver with a diameter of 25 cm is about 490 kilo, which would definitely keep it clamped to the pump-board, and to remove it forcefully would be impossible, or possibly break it. The remedy is, of course, to fill the receiver with atmospheric air to equalize the pressure difference, but this operation is not as simple as it might sound. If a pump-assembly is opened to the atmosphere too abruptly, for example by removing larger parts of the barrel, it would cause a 'wind' into the receiver, which could damage the apparatus inside it, or even blow off the receiver. Without any specially designated method or mechanism to neutralize the pressure difference, a successfully pumped and leak-proof air-pump must have been something like a paradox. The same characteristics that made a good vacuum and a successful experiment possible, also made it difficult and time-consuming to open the pump and prepare for the next experiment. Removing parts for letting in air would, for example, destroy carefully prepared leak-tightenings on pumps that were dependent on cement to keep the vacuum. What was needed was the possibility of making a deliberately controllable leak of air into the pump when the receiver had to be removed, without destroying apparatus inside the receiver, the receiver itself, or carefully prepared seals.

Robert Boyle had been aware of the problem. In one experiment, where he wanted to go from a vacuum towards atmospheric pressure in steps, he let air into the barrel by first removing the brass-peg at the top and then operating the stopcock between the barrel and the receiver (Figure 6, Fig. 1, R and S).[204] He could consequently increase the pressure in the receiver, but this method was problematic. According to his own account, he was able to allow air into the receiver by removing the stopper and turning the vane, but it was difficult to control the amount of in-streaming air. By turning the stopcock a little, air would easily rush into the receiver too rapidly and this could be destructive. He reported, for example, that it happened that air rushed into the receiver with such a force that the mercury in an internal barometer rose much to fast, breaking the top of the glass tube.[205] See Figure 22. The reason for limited control lies in the construction

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[204] *Boyle's Works*, vi, 143.
[205] *Boyle's Works*, i, 195.

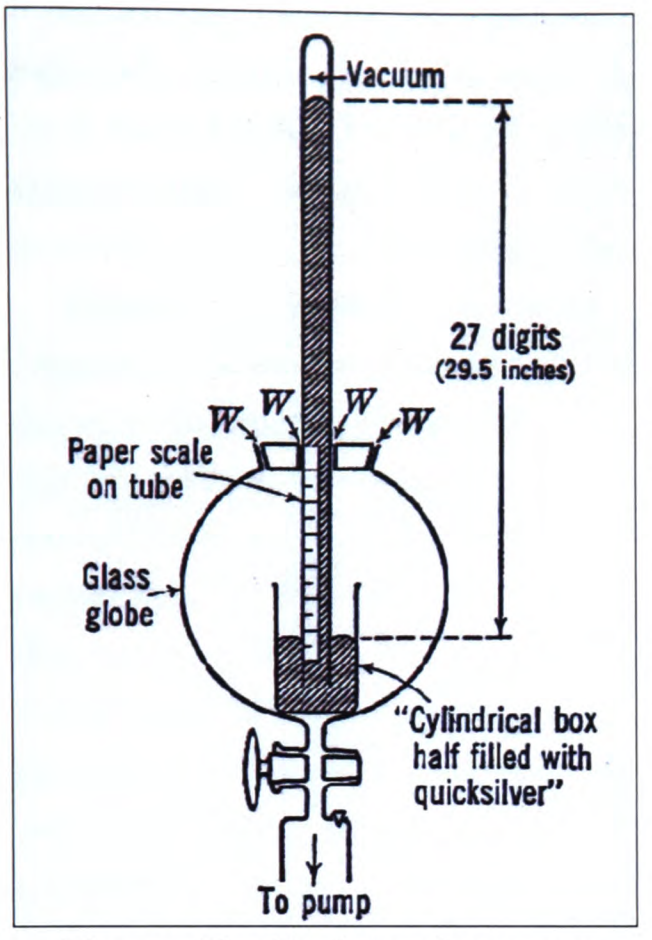



**Figure 22.** Boyle's barometer experiment. The *W*'s indicates fissures closed with Diachylon, which was a sealing agent made from several vegetable juices and lead oxide. Conant (1957), 21.

of a stopcock itself, which has a geometry that makes fine tunings almost impossible. It goes from fully closed to fully open by a 90° turn of the vane, and the effective opening increases most rapidly in the beginning of the turning. This means that a slight movement of the vane makes a large difference at the opening area at the beginning of the turn, and any fine control of the air-stream is impossible.

Hauksbee did not use pegs and stopcocks, and the self-closing valves were unsuitable as air-inlet devices, nor were they accessible from the outside of the pump. If he had instead used a special designated stopcock for the purpose, he would certainly have experienced similar problems to Boyle. The method he came up with was far more advanced than his predecessor's, however. Harris described the solution to the problem in the following way:

> And when the experiment is over, and you would let the External Air return again into the Receiver in order to take off the Engine, you need only unscrew a little the Elbow above-mentioned, by turning the Air pump about from Left-hand towards the Right, as far as liberty allows, and then the Air will easily insinuate it self between the Joints of the Screw.[206]

Hauksbee's technique was very elegant. By moving the pump-barrel horizontally to the right, the elbow that the pump was attached to would become unscrewed a little out of the brass plate. This would give air the opportunity to pass above the gasket and seep into the chamber through the opening that was created between the threads of the brass plate and the mating ones in the elbow. An illustration explaining these details is given in Figure 23. He could therefore easily control the quantity of air leaking in by adjusting the horizontal position of the barrel. The amount was dependent on how far the elbow was unscrewed from the brass plate, and any physical obstruction limiting the horizontal movement of the barrel would limit the flow of air into the receiver. The term 'as far as liberty allows' must therefore have been written with physical obstructions for the barrel in mind, for example the edge of the table if the pump assembly was fastened to one, or a wall if it was mounted in a window frame. It might also refer to the

[206] Harris (1704), under 'Air-pumps'.

freestanding version of Hauksbee's single-cylinder air-pumps.[207] The term is especially meaningful here, since the horizontal movement of the pump-barrel must have been limited by two of the legs, with the barrel sticking out between them. (Figure 16a). Ending the air-inlet process was simply done by turning the barrel towards the left, until the elbow was fully tightened into the brass plate.

Hauksbee's system was much more controllable than Boyle's. The effectual cross-section of the passageway for the in-streaming air would increase in a linear manner due to the geometry of the threads, as the barrel was moved from left to right, Small movements of the outer end of the barrel would give minute variations in the opening between the threads. It would not, as with the stopcock, open abruptly with a small movement of an actuator. Instead it would open slowly and gradually as the barrel was turned, allowing the operator carefully to fill the evacuated receiver with air, and thus avoid breaking the barometer and the receiver blowing off. It supplied the pump with a novel function as well, the 'pressure control', an issue that will be discussed below.

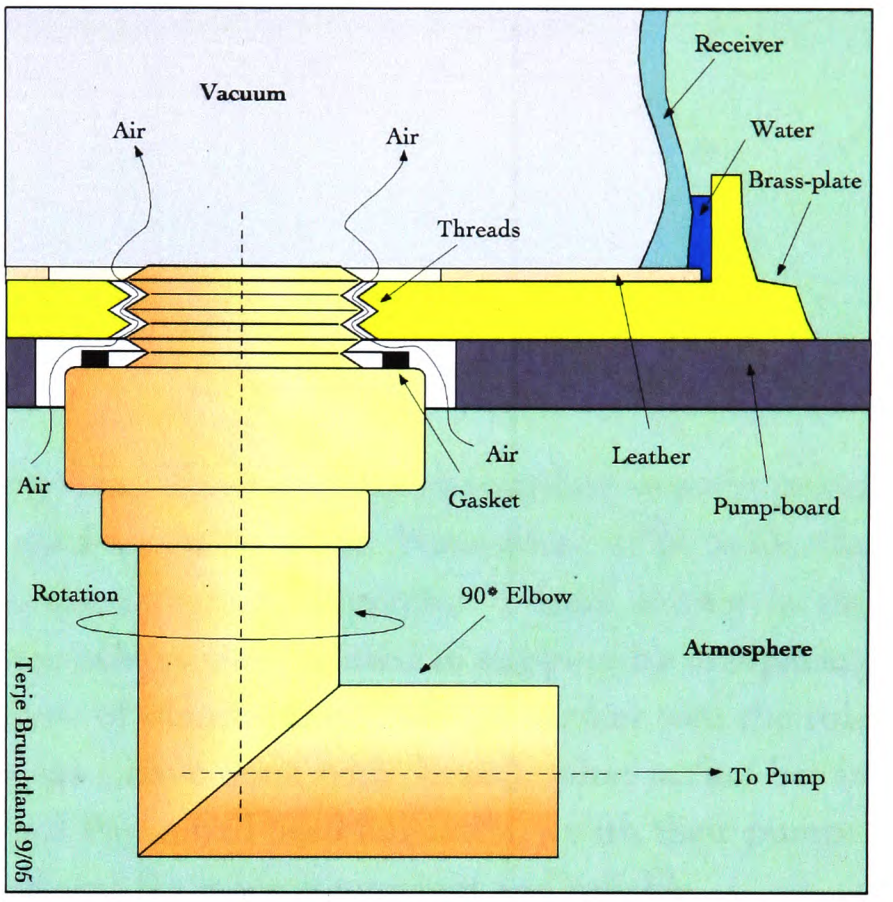



**Figure 23.** The air inlet function. Principle drawing. Air is let deliberately into the receiver along the screw-threads; by turning the barrel to the right (left-hand treads).

Harris also described another way to let air into Hauksbee's pump. After he had described the method above, he added: 'Or you may let the air in also by unscrewing the Cap at P'. This option was, in principle, similar to the first one, working by air deliberately leaking into the receiver along threads, and obtained by unscrewing. See Figure 6 (the small plug on the topmost brass piece on the receiver R must depict the screw). It could, for example, have been an alternative if side-ways movements of the barrel were restricted, as well as used as an additional passageway for air to speed up the venting process, since the opening obtained along threads would never be very big. The possibility of letting air directly into the receiver on Hauksbee's pump is interesting because it has until now been regarded as a much later contrivance. According to one source, valves or stopcocks mounted

[207] F. Hauksbee, 'Several Experiments on the Attrition of Bodies in Vacuo', *PT*, vol. 24, (1705), 2165-75; Tab 2.

directly onto the receiver were not introduced until the late eighteenth century.[208] Even if these later gadgets were often used for applications that where unknown in Hauksbee's period, the function of letting air into the receiver in a controllable way was by then almost a century old.

With seventeenth-century air-pumps in mind, modern authors have raised questions about what the improvement in Hauksbee's air-pump in fact consisted of. The Royal Society described this first pump as a 'new invention', and one novel function on Hauksbee's pump was clearly the capability of a controllable deliberate airflow into the receiver.[209]

## 2.2.3. Exactness

### 2.2.3.1 The barometer

'Exactness' was another quality that Hauksbee emphasised in his air-pump advertisements. The term was used as early as in November 1701 with the combined engine and referred to the attached barometer. I have shown in the previous chapter how the barometer-effects were related to cupping by comparing the elevation of mercury and the flow of blood. Here I will go further into the role of the barometer and demonstrate (as I have done with 'Ease'), what in fact lies in the term 'Exactness'. Both Boyle and Papin had used barometers with their pumps, but I argue that Hauksbee's method was far more convenient and reliable.

Around 1660, Robert Boyle had undertaken some crucial experiments for studies of the weight of the atmosphere by placing a barometer in the pump-receiver.[210] Papin had used barometers inside receivers as well, but since his pumps seem to have had less importance in shaping the image of the air-pump in England during this period, a comparison with Boyle's engines is also the most helpful here. Boyle's barometer arrangement consisted of a straight glass tube, closed at one end and inverted in a vessel with mercury that was placed inside the receiver. The upper part of the tube was sticking out of the receiver-top; and with atmospheric pressure in the receiver, the mercury would rise to the normal height of approximately 29.5 inches and could be watched through the glass-wall of the tube. The mercury would sink and recede inside the receiver during pumping, and set

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[208] W. Hackmann, *Catalogue of Pneumatical, Magnetical and Electrical Instruments* (Museo di Storia della Scienza, Florence, 1995), 54.

[209] The problem of opening a vacuum-system after an experiment is finished is solved today by equipping them with a special valve for the purpose, called the 'vent valve', the 'air admittance valve', etc. See for example T. Brundtland, 'Blåmann, beskrivelse av vakuumsystemet' ['Blaamann, a description of the vacuum system'], *Journal of the Swedish Vacuum Council* (1995); and A. Roth, *Vacuum Technology* (Amsterdam, 1976),122.

[210] *Boyle's Works*, i, 192-201. A comprehensive discussion of this experiment is given by J. B. Conant: 'Robert Boyle's Experiments in Pneumatics', in *Harvard Case Histories in Experimental Science* (2 vols, Cambridge, Ma. 1957), i, 17-30.

close to the mercury surface in the basin when the lowest pressure had been obtained. See Figure 22. In Boyle's early experiments, the behaviour of the barometer itself was subjected to examinations; later he used the barometer as a measuring instrument, for example when he tried to detect ether by dropping feathers in a tall receiver.[211] He had no standard arrangement for connecting the barometer to the recipient, however. The barometer had to be secured with different kinds of mounting gadgets and carefully sealed with cement or sealing wax every time a new experiment was set up.[212] This was a difficult and cumbersome task according to Boyle. After an experiment was over and new arrangements were planned, the barometer had to be disconnected from the set-up by melting and removing the cement, always with the chance of breaking the fragile glass-tube.

It is presumed by modern commentators that Hauksbee was the first to integrate the Torricellian tube into the air-pump in a permanent way.[213] However, I was not able to find any evidence that a general study of this improvement, or its importance for contemporary air-pump practice, had ever been undertaken. I will do it here, and later in the thesis show how Hauksbee's idea of continuously monitoring the vacuum became a characteristic element in pneumatics. It is also commonly thought that it was Hauksbee's double-barrelled pump that was the first to be equipped with this contrivance. It was not, and we must again turn to the first edition of *Lexicon Technicum* for information. Hauksbee gave no details of the barometer in his advertisements for the single-barrelled pump, but Harris described it like this:

> The other Hole hath fastened into it a small Brass pipe, on which is screwed the upper part of the Mercurial Gage, whose use is by rising of the Mercury from the Cistern below into the *Torricellian Tube*, to shew to what degree the Recipient is exhausted. This gage is represented with the letter G.[214]

The main component for obtaining the 'exactness' was therefore a barometer that was placed outside the receiver. It was mounted under the pump board, and connected to the receiver space through the top of the tube.[215] With this construction, the mercury would become sucked upwards to the top of the tube during pumping. At atmospheric pressure, the mercury would stay in the cistern. But as the receiver became emptied of air, the mercury would rise in the tube and approach the 29.5-inch mark as the pressure reached its minimum, forced upwards by the pressure difference between the atmosphere and the receiver pressure.[216] See figure 21.

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[211] *Boyle's Works*, vi, 135-6.
[212] For example with melted 'Diachylon', see *Boyle's Work*, i, 193.
[213] Helden (1991), 166, 172.
[214] Harris (1704), under 'Air-pumps'.
[215] Hauksbee's own description of the barometer was given in *PME* (1709), 3.
[216] Or upwards to the 0-inch mark, if the scale was inverted.

Hauksbee's integral barometer was much more than a fixed and permanent version of Robert Boyle's. The construction was different, which gave it a series of advantages over Boyle's concept (Figure 22). In opposition to Boyle, Hauksbee's barometer did not, for example, take up any space in the receiver, and consequently left it all for the experiments. It was also equipped with a scale, divided into intervals of half an inch,[217] which made it possible to obtain accurate readings of the mercury-height, and consequently the pressure. Boyle had in some experiments glued a piece of paper with markings to the barometer tube, but admitted problems with obtaining accurate readings, especially at low pressures where the mercury had fallen below the top of the receiver.[218] Hauksbee's barometer was also of a safer construction than Boyle's, who had reported accidents where the top of barometer-tubes had been knocked off by rising mercury, due to in-rush of air. Should sudden in-rush of air happen in Hauksbee's pumps, in spite of the sophisticated air-inlet system, the mercury would be forced downwards and into the cistern that would presumable stand the shock better then a glass tube. The openings in the cistern, exposing the mercury to the atmosphere, would in addition act as a 'safety valve', making it possible for the mercury to 'splash over'. Also the problem with air bubbles that occasionally rose through the mercury and accumulated on top of the column in Boyle's barometer would be avoided here. These bubbles caused inaccurate readings when they burst in the space above the mercury. [219] This problem was avoided by the structure of Hauksbee's barometer itself, where possible air bubbles floating up through the mercury would be released into the receiver and pumped away. Finally, the localisation of the barometer under the receiver board also made it less vulnerable to breakage by accidents, especially with the freestanding model where the four legs would protect it (Figure 16).

With Hauksbee, the barometer was no longer a device put up for a particular experiment, but had become a measuring instrument that was permanently connected to the air-pump. What he did was to 'institutionalize' the barometer into a fixed and permanent measuring device, and this was therefore a great step forward in the process of making the air-pump into a laboratory instrument.[220] This was yet another function of Hauksbee's air-pump that his contemporaries appreciated.

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[217] Obtained from a close study of the illustration in Figure 6.
[218] *Boyle's Works*, i, 193.
[219] Ibid, 194.
[220] Like the air-inlet valve, this is now standard on all modern vacuum-systems. See note 209.

### 2.2.3.2 Pressure control

Another important advantage of Hauksbee's air-pumps was based on a combination of pumping, barometer readings, and the air-inlet function. He had made pumping easy by the self-closing valves and made it possible to monitor the pressure by the permanently attached barometer. He had also found a convenient and safe way to let air into the receiver. By applying all these three functions, it became possible to perform series of experiments under controllable conditions. Successive experiments, performed under the same particular pressure could be made, as well as experiments where regulated variations of the pressure were the objective.

In experiments where the exact pressure was of importance, it could not have been straightforward to hit the intended reading on the barometer scale by simply making the right number of plunger strokes. This was due to the nature of the medium, air, itself. Air is an elastic substance that needs some time to leave the receiver. To know exactly when to stop pumping in order to achieve the proposed height of the mercury column would have been difficult. Minor, uncontrollable leaks and evaporations from various materials inside the barrel and the receiver would always make a small pressure increase after the pumping had stopped. For example, if an experimenter was aiming at a particular reading on the barometer scale, he could operate the plunger while observing the mercury, and stop when the intended pressure was approached. If the reading stabilized at a lower value (at a pressure too high), he could carefully draw the plunger outwards, until the right mark was reached. If, however, it stabilized at a higher reading (lower pressure) than aimed at, he could simply let air into the receiver by moving the barrel carefully to the right, watching the mercury column sink, and close just when the right level was reached. The pressure in the receiver could thus be lowered by pulling the barrel-plunger, and raised by moving the barrel a little to the right.

These possibilities, combined with the observance of the built-in barometer, made Hauksbee's first air-pumps into a versatile instrument for performing reproducible experiments, where the experimental conditions could be controlled and recorded.

## 2.3 Conducting experiments

The best illustration of the superiority of Hauksbee's single-barrelled pump comes from reports about its use. This section is a review of instruments, methods and practice that were available with the single-barrelled air-pump, before the introduction of the classic model. A survey of these issues is required to understand the status of Hauksbee and his instruments at the time when he came to the Royal Society.

### 2.3.1 Early air-pump accessories

An issue that will become manifest through the second half of my thesis is that successful air-pump experiments are not dependent on well-functioning pumps only, but also on various sorts of additional equipment. Generally, a whole range of reliable devices for use both inside and outside of the receiver are needed. I will here show that Hauksbee's early efforts of developing the air-pump into a practical instrument was not just concentrated on easy pumping and pressure monitoring, but also on making efficient pump-appurtenances. It is clear (Chapter 1) that as early as November 1701 he had developed accessories for both high-pressure and anatomy applications of the multipurpose engine. A similar survey of air-pump appurtenances in the period when he entered the Royal Society is likewise necessary to understand his engagement in pneumatics at that stage, as well as the potential of the single-barrelled pump. Hauksbee did not mention any air-pump accessories for use with the multipurpose engine in particular, but a year later, in October 1702, he informed his customers that the air-pumps could be delivered with 'apparatus for making all sorts of experiments proper to be made in Vacuo Boyliano'.[221] Later he announced apparatus useful for 'Pneumatical Experiments'.

As in the previous discussions, *Lexicon Technicum* acts here as an excellent source for confirming and explaining Hauksbee's advert-claims. It contains a description of an apparatus for use with the pump, apparently from the end of 1702. Both Boyle and Papin had described various sorts of apparatus to be used with their engines, and it is rather likely that Hauksbee had been aware of this. Harris claimed that Hauksbee's single-barrelled air-pump was superior to all earlier pumps, and one of the reasons could have been a gadget for manipulating objects in the receiver. In addition to the air-pump assembly, Harris gave a sketch of a separate receiver (Figure 6, *R. 2.*). The purpose of engraving this extra item on the plate must have been to show the contemporary status of the air-pump, and he described it like this:

[221] *The Post Man*, 27 Oct (1702).

R.2. is another Receiver through whose Cap P (which contains a box in which several Collars of Cork and Leather) passes a Brass Wire as W, movable up and down in the Cap, without letting in any air into the receiver, and on whose a hook K may any thing be suspended or fastened in an Experiment.[222]

With such a device, the operator could change the vertical position of an object inside the evacuated receiver without air leaking in. Even if it is not particularly mentioned, the construction must also have facilitated rotation of objects, since the brass wire that pierced the leather-collars had to be circular and smooth to avoid leaks. In practice, the success of an air-pump experiment will often depend as much on the quality of such devices as the pump itself. For example, if the leather collars were made too loose, the brass wire could easily be pulled up and down and rotated, but air would leak in and destroy the vacuum. If it was too tight, the wire would be difficult or impossible to move.

It is interesting to observe that the self-standing version of the single-barrelled pump (the fifth type) is depicted as part of an experimental set-up for rotating objects inside an evacuated receiver. See Figure 16 a, *i*. It is found in Hauksbee's first article on the attrition of bodies, where he rubs objects of different materials against each other in vacuum.[223] In that experiment, the rotational motion was transferred from a large wheel into the receiver by a rotating spindle, going through a brass box with leather collars. Such 'chafing' experiment came to play an important role in Hauksbee's work on electricity, for example. It is therefore clear that one crucial component in these experiments, the rotatable 'feed-through', was developed early, presumably in 1702, and was included in Harris's appraisals of the pump.[224]

In addition to Harris, there exist a few other sources with information about Hauksbee's air-pump appurtenances prior to the double-barrelled pump. One place is the 'Journal Book' of the Royal Society. It contains a series of short entries about the experiments that Hauksbee made there, which consequently points to the instruments he must have had developed at that stage. The pieces of equipment he used were, for example, square glass-phials to be broken by pressure differences on the inside and outside, for showing the weight of the atmosphere and the spring of the air. Special truncated brass-cones and thin glass-plates were used for the same purpose, as well as inflatable bladders for lifting up weights in vacuum. He also described smaller, interconnected receivers for experiments with vacuum and pressurized air on birds, and arrangements for suspending a bell inside a receiver. Further, he used equipment used for refuting the 'funicular hypothesis', as well as more complicated mechanisms for dropping coins and feathers inside a tall, evacuated receiver. The most advanced instrument that Hauksbee described in this

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[222] Harris (1704), under 'Air-pumps'.

[223] F. Hauksbee, 'Several Experiments on the Attrition of Bodies in Vacuo', *PT*, vol. 24 (1705), 2165-75; Tab 2.

[224] In modern vacuum technology, a such device is called a 'combined linear and rotary vacuum manipulator', or 'feedthrough'.

period was probably a contrivance for dropping like-quantities of gunpowder onto a red-hot piece of iron inside a receiver, in order to study the role of air in combustion.[225] See Chapter 4.

Another source is the newspaper advertisements from December 1704 and January 1704/5 by the mathematician James Hodgson. They describe a series of public lectures on natural philosophy, including pneumatics, which whould start in January 1705.[226] Is clear from the note that Hauksbee's 'improved air-pump' and various accessories were going to be used. Four sorts of air-pump experiments were mentioned, as he planned to demonstrate the weight and elasticity of air, and the importance of air for the propagation of sound and the life of animals. These were some of the experiments that Hauksbee had earlier made at the Royal Society, now ready to show that his equipment could also work in more public demonstrations. Such lectures came to play an important role in Hauksbee's later career, and will be further discussed in Chapter 4 and 5.

The extent of Hauksbee's engagement in pneumatics becomes clear from these experiments, showing that, in this period, he had already established himself as an excellent instrument-maker, supplying air-pumps and air-pump accessories for both public and private demonstrations, all before the double-barrelled version was in sight.

### 2.3.2 Experimenting pace

In addition to general matters like ease and exactness, other issues that characterise the qualities of an air-pump are, for example, 'leak-tightness', 'pumping capacity, 'pumping speed', and 'lowest attainable pressure'. The first of these concepts are discussed above, the others will be treated in depth in the next chapter. Here I will introduce yet another concept, 'experimenting pace', which will be helpful when we try to understand the advantages of Hauksbee's single-barrelled pump. It is an overall concept that indicates how easy an instrument is to use; and is relevant to most experimental activities. Applied to seventeenth- and eighteenth-century pneumatics, it describes the speed or rate at which subsequent air-pump experiments could be made. In addition to the time needed for performing the experiment itself, it includes the time used for sealing off the receiver, as well as the pumping action (described by the concepts given above), and subsequent venting (equalizing the pressure) when the experiment was finished; and also the necessary preparations for the next test.

In Hauksbee's case, the time for preparing an experiment had been reduced considerably by the use of wet leather gaskets, instead of cumbersome cement or sealing wax. This was a great advantage when an experiment was over as well, since no time was needed to break and remove the sealing agent when the receiver

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[225] These experiments are described in the 'Journal Book' from January to December 1703.
[226] *The Daily Courant*, 9 Dec (1704).

was removed. The time used for pumping was also reduced. For Boyle, pumping-speed had not only been determined by the time required for driving the crank back and forth but also the time used for opening and closing the stopcocks and handling the stopper between the strokes. This was shortened to a minimum by Hauksbee's use of self-closing valves. Finally, with Hauksbee's single-barrelled pump, it was only necessary to turn the barrel sideways to obtain quick and safe 'airing' of the receiver when an experiment was over.

The experimental pace, together with convenient pump-accessories and pressure monitoring were all necessary to give Hauksbee's single-barrelled pump its reputation, and produce the appraisals from his contemporaries. They contributed to make pneumatic experiments less time-consuming, easier and more accurate; and most importantly, they made air-pumps operational for non-specialists. The last issue will be discussed below.

### 2.3.3 Practical pneumatics

I will here give an example of how the issues discussed above facilitated convenient and reproducible experiments, and thus laid a foundation for uses of the air-pump like that depicted by Wright. For this purpose I will review an article on motion of pendulums in vacuum by the Reverend William Derham. Published in December 1704, it is the first report on experiments where a Hauksbee-pump was used, undertaken by another actor.[227] Air-pump experiments of the early eighteenth century are normally thought of as demonstrations of known facts,[228] but it is striking that this first 'non-Hauksbee' account represents another issue, basic research. It gives us a unique look into 'practical pneumatics' at the time. This is important, because it demonstrates the present level of air-pump technology as well as indicating the pump's potential as a research instrument. It also, as I will show, confirms many of my claims set forth above.

William Derham had earlier used Hauksbee's condensing-engines and air-pumps to study effects of compressed and diluted air on sounds and animals.[229] We know that the air-pump experiments on animals were performed in September and October 1704,[230] and about the same time he tried to solve a problem that had occupied him for a long time. He was curious to know whether or not there was any difference between the pace of a pendulum clock in open air and in a vacuum. Hauksbee had earlier performed this experiment in the Royal Society, but Derham preferred to make series of similar tests during an extended period by himself. Both technical and operational details can be extracted from the paper when it is read with questions about pneumatics in mind. Derham described the pump that Hauksbee generously had lent him in the following way:

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[227] Derham (1704), 1785-9.
[228] Helden (1998), 19.
[229] Derham (1714), 5, 8, 132.
[230] Ibid, 8,

his Air Pumps exceed others in the Ease of being pumped, and in the Certainty of their Evacuation; which may be known to a great nicety.[231]

This was written in 1704, before the double-barrelled pump was available. It becomes clear that Hauksbee had several pumps in stock at the time, supposedly all of the single-barrelled kind. Derham was convinced that Hauksbee was the best maker of air-pumps in the world. Thirty years later, when pneumatics had developed much further, he still described Hauksbee's air-pump from 1704 as 'excellent.'[232]

It is interesting to observe that Derham emphasised 'easy pumping' and the 'certainty of evacuation' (to know the pressure) in his account of 1704, issues that perfectly correlate with Hauksbee's 'ease and exactness'. This shows us again, as I did above, that the terms have to be more than advert-boasts from Hauksbee, and describe factual properties of the single-barrelled pump.

A few technical details about the pump become clear as well. Derham must have been able to work with tall receivers, since he tested timepieces with 10-inch pendulums swinging under the clockwork, suggesting a receiver of at least 15-20 inches height. This demonstrates that the pump could evacuate and maintain a low pressure in large receivers. He reported that the pendulums swung with greater amplitude in vacuum than in open air, causing the clockwork to go slower. Sometimes the amplitude was about the same as in open air, however,[233] which he explained was to be made by 'some of the fouled oil, spirtling on the wheels when letting in air.' This means that oil must have spurted up and out of the elbow below the pump plate and onto the gears when the barrel was turned sideways for letting in air, which tells us that the seals and the valve-flaps were lubricated with an abundance of oil (Figure 11 and 23).

Moreover, in addition to revealing technical details, these notes are also saying something to us about how convenient and practical it was to use the pump. Derham wrote that the conclusion from one series of experiments was based upon 'the result of many repeated Experiments, day after day.' Each of these tests could last up to 4 or 5 hours, which demonstrates that the pump must have stayed leak-tight and kept its vacuum for this period. It also means that it was so reliable and stable that new experiments, under the same conditions, could be repeated the next day. Derham also wrote about a series of experiments that were 'repeated divers times with the same success.' This points to another issue in experimental philosophy, reproducibility. If the results of an experiment are going to be accepted, it must be possible to repeat the experiment and obtain the same results. This depends on several factors, for example that all the tests are made according to the same plan, as well as on the quality of the instruments. If the equipment should

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[231] Derham (1704), 1786.
[232] W. Derham, 'Experiments concerning the vibrations of Pendulums', *PT*, vol. 39 (1735), 201.
[233] According to Derham, the 'force of the Spring on the Pallets was blunted'.

fail, or its parameters change during the test, the following results will be useless. According to Derham, this was not the case with Hauksbee's single-barrelled air-pump.

Another example of Hauksbee's ingenuity is found in some experiments where Derham wanted to study the relationship between the amplitude of the pendulum-swing and the surrounding air-pressure. He first started by checking the amplitude at a pressure close to the atmosphere (6" high in the pump-barometer), and then evacuated the receiver more or less fully, before he let air into the pump again. In the first case he observed that the swing was only a little larger than in open air. When starting from a low pressure, he noted that:

> the pendulum vibrations gradually decreasing, according to the quantity of air readmitted.[234]

This must imply, first, that he was able to reach an intended pressure and keep it stable for more than an hour (he gave the delay at 6" to be about half a second per hour). Second, that he used the air-inlet facility to increase the receiver-pressure in a controlled way, allowing time to observe the decrease in amplitude as the pressure became augmented towards atmospheric pressure. Since each observation required a considerable amount of time, it points to a procedure where he let in air, stopped at distinct pressures and observed how the pendulum stabilized at new and smaller amplitudes; before he again allowed more air into the receiver for new tests. I have already described such a procedure above (see 2.2.3.2 Pressure Control, page 94), and here it is confirmed by Derham as a possibility stemming from the combined use of the pump, the barometer and the air-inlet facility. Thanks to this, Derham was able to perform his experiments at controllable and distinct pressures.

There are no signs in the text of any actors in these undertakings other than Derham himself. This means that he must have been able to perform the experiments alone, without any support of a helper or technician. Derham said that he distrusted neither Hauksbee's 'skills nor fidelity' when the latter had made the tests, but that he was desirous to try them himself. This became possible by 'Hawksbee's generous kindness, in lending me [Derham] one of his air-pumps'.[235] In these experiments, the attention was clearly diverted from the pump to the effects of it, like in Wright's painting.

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[234] Derham (1704), 1788.
[235] Ibid, 1785.

## 2.4 Black-boxing the air-pump

It is now time to comment on Shapin and Schaffer's account of when and how the air-pump left the stage of being a problematic prototype to become a stabilized, common commodity.[236] In the 1670s, they write, 'the air-pump gradually changed from being a restricted property to a few privileged individuals, to becoming a commercially available article'.[237] They underpin this view by showing the status that the air-pump had achieved among natural philosophers in Holland and in France, and that a market for such instruments had developed; a process in which Papin is given a crucial role. The pump is described as 'an unproblematic resource and no longer an assemblage of controversial theoretical and practical components'. They do not apply the concept of 'black-boxing' to the various aspects of the air-pump in this period, but their message is often referred to as such, for example by Golinski.[238]

Though they are not very clear, the impression gained from the actual section in *Leviathan and the Air-pump* is that the air-pump had become black-boxed and commercialised also in England in this period. They make a connection between the advance of the air-pump on the continent and its development in England by showing that Papin had built the double-barrelled pump while working for Boyle, and that this knowledge could have been transferred to Hauksbee. Similar ideas are also expressed by the editors of *Boyle's Works,* who write that Papin's double-barrelled pump superseded the previous ones, and that air-pumps generally had become cheaper and more widely available.[239] They do not supply any new evidence, however, but refer back to *Leviathan and the Air-pump.*

It is at this point that I disagree with Shapin and Schaffer. I cannot see that the air-pump had become black-boxed and commercialised in England in this period. I will instead argue that a similar development that took place in Holland and France did not happen in England until thirty years later, then with Hauksbee at the helm. Based on my discussion earlier in this chapter, I will further argue that the role of Papin's pump in this process was not as important as indicated in *Leviathan and the Air-pump*. I do not say that the pump had no influence on Hauksbee's ideas at all, but its overall importance can definitely be questioned, an issue I will come back to in the next chapter. The status that this pump holds in the story of the English air-pump is still part of the 'great confusion', as described by Wilson in 1848.[240]

If we stick to the term 'black-boxing', I will argue that the English air-pump did not become black-boxed in the technical sense by either Boyle or Papin's pumps, but approached that level by the until-now unknown, single-barrelled air-pump

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[236] I distinguish between instruments in the 'black-boxed, and the 'stabilized form'. See Chapter 3.
[237] Shapin and Schaffer, 274-6.
[238] Golinski (1998), 133-61.
[239] *Boyle's Works*, vol. ix, p. xxii.
[240] Wilson (1849), 330–54.

designed by Francis Hauksbee in 1702. The air-pump might have been black-boxed in the *conceptual* way in the 1670s, when it became commonly accepted as a device for producing matters of fact, and when the previous controversies over the validity of its results had ended. The *instrumental* side of the process, to make the pump into an instrument that could be used without paying much attention to how it worked, had to wait for Hauksbee.[241]

A discussion of this process, leaving aside Papin's device for a while, is required if we want to understand the full impact of Hauksbee's first air-pump. First, the various tasks that Boyle's technicians had to perform, like the preparing and applying of sealing wax and the opening and closing of stopcocks had been eliminated by the way Hauksbee's machine was constructed. In some sense we can say that Hauksbee had built the functions of these operators into the device, especially regarding the stopcocks. The use of gaskets instead of sealing wax can better be described as surpassing a problem through new technology. He had in this way eliminated a great amount of tacit knowledge that clearly must have been present with Boyle's technicians.[242] For example, it is clear (I am here using self-experienced familiarity with such tasks) that the process of applying sealing-wax with a hot iron required both 'gestural knowledge' about how to use the hands, as well as judgment of the right temperature of the iron.[243] The nature of such operations, which are built on inputs from the senses as well as experience and physical practice, is of a kind that is impossible to fully express in writing. Boyle had tried to describe such tasks with long texts, but if another actor should successfully replicate his experiments in a similar pump, this particular skill was of a kind that only could be achieved by trial and error. Tacit knowledge is one factor that has to be eliminated during a black-boxing process, where the required skills are either made automatic or surpassed by more convenient technology.

Another characteristic of a black-boxed instrument is the non-appearance of technicians. In the case of the air-pump, Boyle had depended on a series of technicians to run his laboratory and undertake the experiments. Even though these technicians were not explicitly mentioned in the texts, a fact that reflects their social status, we know they were crucial in performing experiments, for example in the preparation phase, when the pump-assembly was sealed off with wax. Technicians normally undertook the pumping and terminated the tests by removing the receiver and dismantling the equipment. Their importance, as well as their anonymity, is discussed by Shapin, who named them 'the invisible technicians'.[244] The absence of technicians in Boyle's, and in Hauksbee and his followers' writings

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[241] For a discussion of conceptual vs. instrumental black-boxing, see: T. Nickles, 'Justification and experiments', in Gooding (1989), 311.

[242] For a general account on tacit knowledge see: M. Polanyi, *Personal Knowledge* (1962) and *The Tacit Dimention* (1966).

[243] T. Brundtland, 'Restoring the greatest vacuum chamber', in Brundtland (1997), 65-8. The term 'gestural knowledge' is a concept in: O.H. Sibum, 'Reworking the Mechanical Value of Heat', *Studies in History and Philosophy of Science*, 26 (1995), 76.

[244] Shapin (1994), 355.

are striking, but have very different reasons. For Boyle, the technicians were crucial, but were not mentioned explicitly because of their low social status. For Hauksbee, technicians were not necessary at all, because he had managed to incorporate their functions, experiences and tacit knowledge into the various technical solutions of his pump. By using an extended concept of instrumental black-boxing, where the process also includes the elimination of helpers by automatizing their work, we can say that Hauksbee's single-barrelled pump, but not Boyle or Papin's, had reached such a level. A good example in Hauksbee's case is Derham's use of his first pump.

Finally, if an instrument is to be declared as fully black-boxed, it should be accessible to larger groups. According to Pinch, one consequence of the black-boxing process is simply lower price and an increased availability of the instrument.[245] As accounted for above, no air-pump was made or advertised for sale in England before Hauksbee, and no import of, for example, Dutch air-pumps took place in this period either.[246]

The first commercial, black-boxed air-pump in England was therefore Francis Hauksbee's single-barrelled pump, announced for sale for the first time in October 1702.

## Conclusion

This is the story of Francis Hauksbee's unknown air-pump. Only one Hauksbee-pump has been known until now, the classic, freestanding double-barrelled model. I have here discussed its predecessor, the single-barrelled pump, which was developed from cupping-syringes.

It was this model that Hauksbee brought to the Royal Society for his first demonstration, and which received appraisals from his contemporaries. One of them, by James Hodgson, described Hauksbee's pump as 'improved'. The historian Richard Westfall, believing that it was the double-barrelled pump being addressed here, and that this pump was a further development of Papin's, has said that no one today (1995) seems able to explain what these improvements in fact consisted of.[247] This is exactly what I have done in the present chapter. First, I showed that this and other judgments were directed to Hauksbee's single-barrelled pump, and then that his contemporaries compared this pump to Boyle's pneumatic engines, and not to Papin's double-barrelled model. Papin's pump seems not to have been

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[245] Pinch (1986), 214.
[246] de Clercq (1997), 151.
[247] See: R. Westfall, (ed.), *The Galileo Project*, http://galileo.rice.edu/Catalog/NewFiles/hauksbee.html

considered as significant by the experimental philosophers of the period as commonly believed today.

The improvements consisted of in-built, self-closing valves (transferred from the cupping utensils) instead of stopcocks and stoppers, elimination of sealing-wax by leather gaskets, a permanently attached pressure indicator, and a facility for letting air into the receiver in a safe and controllable way.

I have also shown how Hauksbee's air-pump made experimenting easy, by examining the first report about such experiments undertaken by an independent actor, William Derham. His account illustrates how Hauksbee's 'improvements' had automatized various tasks that Boyle's assistants had to perform. In Derham's case, presence of any constructor or operator was no longer needed since their responsibilities and experiences had been built into the pump.

Such issues are often referred to as black-boxing, and I showed that this process did not reach the end in England before Hauksbee put his single-barrelled model on the market in 1702. The distance between Boyle and Derham's experimental accounts seems great. The distance to Wright's depiction of an air-pump experiment is even greater, but an important step on the way was Hauksbee's first model, which raised air-pump technology to a new level.

# Chapter 3
# The double-barrelled air-pump

## Introduction

This chapter is about Hauksbee's double-barrelled air-pump. On 1 May 1705, the London public could read the following announcement in *The Post Man:*

> Hauksbee's new Pneumatick Engin or double Barrel Air pump, which will perform all manner of Experiments proper to be made in Vacuo Boyliano with the greatest ease and expedition, it making a continue'd Execution during the Operation. And wheras all other Air pumps, the nearer in their work they approach a Vacuum, the greater their Labour, his the contrary, for at such since the Pressure of the Atmosphere upon the descending sucker, is equal to the Power requir'd to elevate the other. Also his Engin, which is a small Air pump, applicable to Glasses for the new and most approved way of Cupping, performing it without Fire, lamp and Mouth-suction. The Glasses are of several forms and sizes, suitable to any part, and the Operation so easy, any Person upon sight capable of them. Likewise his scarrificators, one of which at once makes 10, another 16 effectual Incisions, also Syphons and Blow Pipes with valves for Anatomical Injections. These Improvements, with Directions how to use and order on all occasions, sold only next Door to Gray's Coffee-house in Gilt-spur street without Newgate, by F. Hauksbee, Author of them.[248]

This is the first sign of Hauksbee's double-barrelled air-pump that has been found. The present chapter is a study of this pump and how it became incorporated into Hauksbee's other activities, as well as its role in the 'black-boxing' and 'stabilizing' process of the eighteenth-century air-pump.

Hauksbee's double-barrelled air-pump (the classic model) is well known to modern instrument-historians. Most of what is known comes from Hauksbee's own book *Physico-Mechanical Experiments* from 1709 (reprint 1719), and from information obtained by examining the few surviving exemplars in museums and

[248] *The Post Man*, 1 May (1705).

collections. See Figure 24. The pump is a masterpiece, a stunning construction with ornaments and beautiful woodcarvings, and it is not difficult to see why it has attracted so much attention. I have in the two previous chapters explained the development of the classic's predecessor, the single-barrelled pump, and how this one was developed from smaller cupping-pumps. However, by searching for the roots of the double-barrelled pump, it became clear that there is in fact little contemporary material about this pump itself. The advertisement quoted above has not been known to modern authors before now, and little can be found about the pump in traditional sources like the 'Journal Book', the *Philosophical Transactions*, and the public-lecture advertisements. If the qualities and status of Hauksbee's double-barrelled pump were as great and important as modern historians have thought, why are there so few traces of this in the contemporary writings? When it was introduced in May 1705, Hauksbee was well into experimenting and publishing, but little can be found in his own writings about the new pump and how it was implemented into his current activities. None of his contemporaries commented on it either. I will therefore argue that the importance of this pump was not as great as it is assumed today, and that the single-barrelled model alone was sufficient to give Hauksbee the status of an outstanding air-pump maker.

First I will conduct a comprehensive examination of the double-barrelled pump and show that although it contained elements from Boyle and Papin's pumps, other crucial issues like reliable valves, sealing methods, and pressure measurements were transmitted from his smaller pump. Further, I will make a comparison of the two Hauksbee-pumps and show that the larger pump did not necessarily facilitate more advanced experiments than the smaller version. Finally, I will claim that while the English air-pump became black-boxed in the instrumental sense with Hauksbee's single-barrelled pump, it reached its stabilised form with the classic model.



**London**
The Royal Society

**England**
Private collection

**Oxford**
Museum of the History of Science

**Munich**
Deutsches Museum

**Padua**
Museum of the History of Physics

**Edinburgh**
The Playfair Collection

**Figure 24.** Six extant double-barrelled air-pumps of Francis Hauksbee's design.

## 3.1 How it worked

Newspaper-advertisements have previously been one source for studies on Hauksbee. His role as a public lecturer in particular has been studied from such notices, most of them found in the first daily newspaper in England, *The Daily Courant*.[249] However, the fact that he at the same time advertised series of instruments in another paper, *The Post Man*, thus keeping advertisements for lectures and instruments separate, seems to have been unknown and not been commented on before. Together with his account in *Physico-Mechanical Experiments*, these announcements make a good starting point for a discussion of the double-barrelled pump and its applications.

I have pointed out earlier that Hauksbee revealed rather few technical details in his advertisements, either because he regarded them as trade secrets, or simply because he had to pay for each of the printed words. But when he announced the double-barrelled pump, after an advertising-break of some months, he did not fail to elaborate. In the advertisement of 1 May 1705 (given above), he gave a detailed description of the principle behind the pump, including the advantages of the two barrels or cylinders. As an instrument-maker, it must have been natural for Hauksbee to let the public know about his new construction in this way, and the text gives some valuable hints about the present status of the air-pump. In all later advertisements, he used the expression 'Air-pumps, both single and double Barrelled', together with announcements of series of other instruments and utensils.[250] Further details were not revealed before his book was issued in 1709, which contained a comprehensive description of the pump, including the way it worked and information on cylinder-volume and barometer accuracy. The first advertisement contained a few expressions that resembled those found with the single-barrelled pump, as the new model was said to 'perform all manner of experiments in Vacuo Boyliano with the greatest ease and expedition'. In the previous chapter I used the terms 'ease' and 'exactness' to contrast Hauksbee's pumps to those by earlier makers. In the following, I will use a similar scheme to describe and explain his double-barrelled model.

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[249] See: Morton and Wess (1993). *The Daily Courant* was first published 11 March 1702.
[250] *The Post Man*, 27 Sept (1705),

## 3.1.1 Ease

### 3.1.1.1 Pumping

The most distinctive feature of Hauksbee's classic air-pump was the arrangement of the two barrels. A common problem for early air-pump constructors, in their attempts to create an artificial vacuum, was how to overcome the forces of the surrounding atmosphere.

The atmosphere exerts a pressure of approximately 1 kg per $cm^2$ on all things and in all directions. This is easily experienced by the force that is felt withholding a plunger of a single-barrelled air-pump when it is pulled outwards. This force can be considerable in larger pumps. There had been many attempts to solve this problem since Guericke's first pumps fifty years earlier. The rack and gearwheel system of Boyle's two first pumps, adopted by Huygens and Senguerd, required much less force than a direct pull on the piston. Denis Papin, while working with Huygens, preferred another solution: his pump forced the piston down and out of the cylinder by an attached stirrup, applying the foot and also body weight.[251] A late version of this pump is shown in Figure 25.[252]

Papin's next contrivance in the field is well known to modern commentators. The double-barrelled pump (1676) had, as its name says, two barrels, where the pistons were interconnected by a system of ropes and pulleys and driven by an operator applying his bodyweight on two stirrups. It was equipped with self-closing valves in the pistons and the barrels, which eliminated the manual-operated stopcocks. See Figure 4. A great advantage here was the effect that took place when a piston had been pulled out and a vacuum created below it: when the pulling force was released, the external air would push this piston into the cylinder again, and the other piston would be pulled upwards by means of the interconnecting rope, performing a new pumping stroke.[253] This construction has traditionally been seen as crucial for the general development of the air-pump, and it is commonly assumed that Hauksbee's double-barrelled pump was a further improvement of this machine.[254] In the previous chapter I raised questions about this belief, and will come back to the issue later. However, it is clear that the function of the interconnected pistons was the focus of Hauksbee's first advertisement. What he emphasised there was the continued operation, and that labour diminished as a vacuum was approached, due to the mutual operation of the two pistons.

The account that Hauksbee gave in his book was much more detailed, however. An illustration was provided as well, which has become the classic image of Hauksbee's air-pump, still used in numerous publications. See Figures 5 and 24. His solution was more elegant and convenient that Papin's: instead of stirrups, which required the full and continuing activity of one man, Hauksbee had

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[251] Helden (1991), 161, and 165.
[252] Papin (1687), 44-7.
[253] *Boyle's Works*, ix, 143-6.
[254] H. Guerlac (1964), 241.

developed a system with a gearwheel and two racks, each connected to a piston. In this way he had actually combined the drive mechanisms of Robert Boyle's pumps with the concept of Papin's two interconnected pistons. A functional diagram is given in Figure 26.

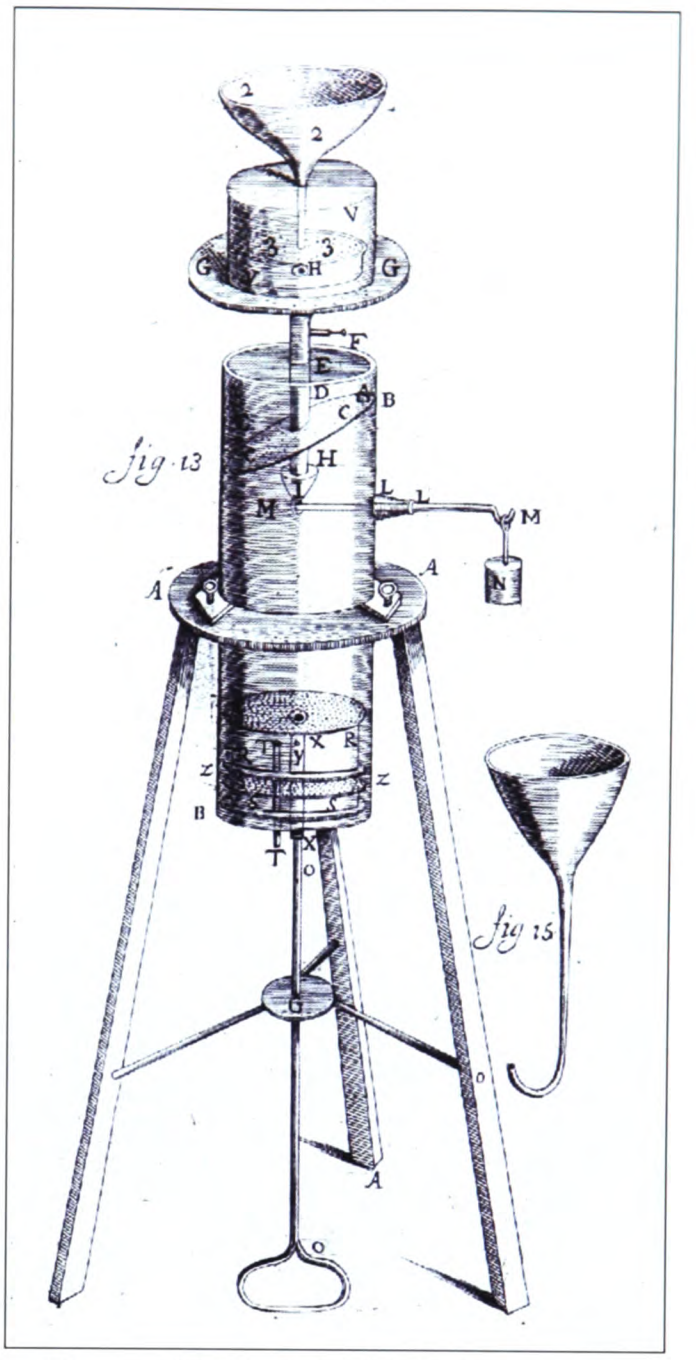



**Figure 25.** Papin's third air-pump, ca. 1687. *A Continuation of the New Digester* (1687).

The gearwheel was placed above the barrels, and the pistons were mechanically interlocked to each other through the wheel and the racks. There was a self-closing valve in each piston, and one at the bottom of each cylinder. These valves functioned in the same way as those of the single-barrelled pump, opening and closing automatically due to the difference in air-pressure on each side of the valve-flaps. Pumping was executed by turning the gearwheel back and forth with the crank, causing up- and down-movements of the pistons. When the operator pulled the crank-handle towards him, he would cause one piston to be pulled upwards and thus perform a pumping action. The piston-valve would close and the one in the bottom open, and air would become sucked out of the receiver through the connector-tube. In the other barrel, the piston would be pushed down; the valve in the bottom would close and the one in the piston open, releasing air that was sucked out of the receiver during the previous stroke. When the crank was pushed back to the start position again, the same would happen (but in opposite order), performing another pumping operation. Consequently, the experimenter had to overcome only the difference of the forces on the two pistons. Approaching the lowest pressure, the only resistance to manage was not much more than the friction of the mechanical parts of the engine. See Figure 27.

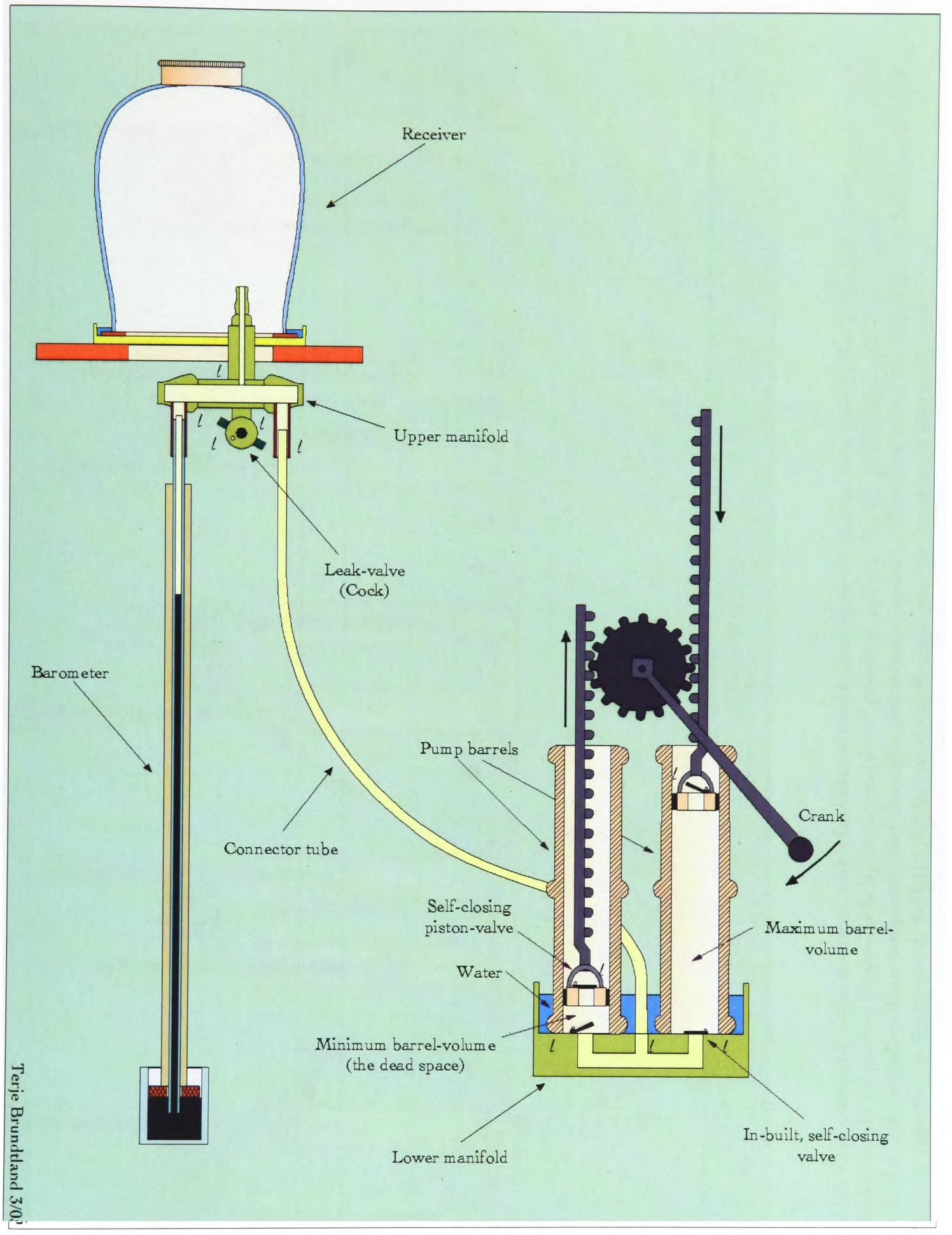
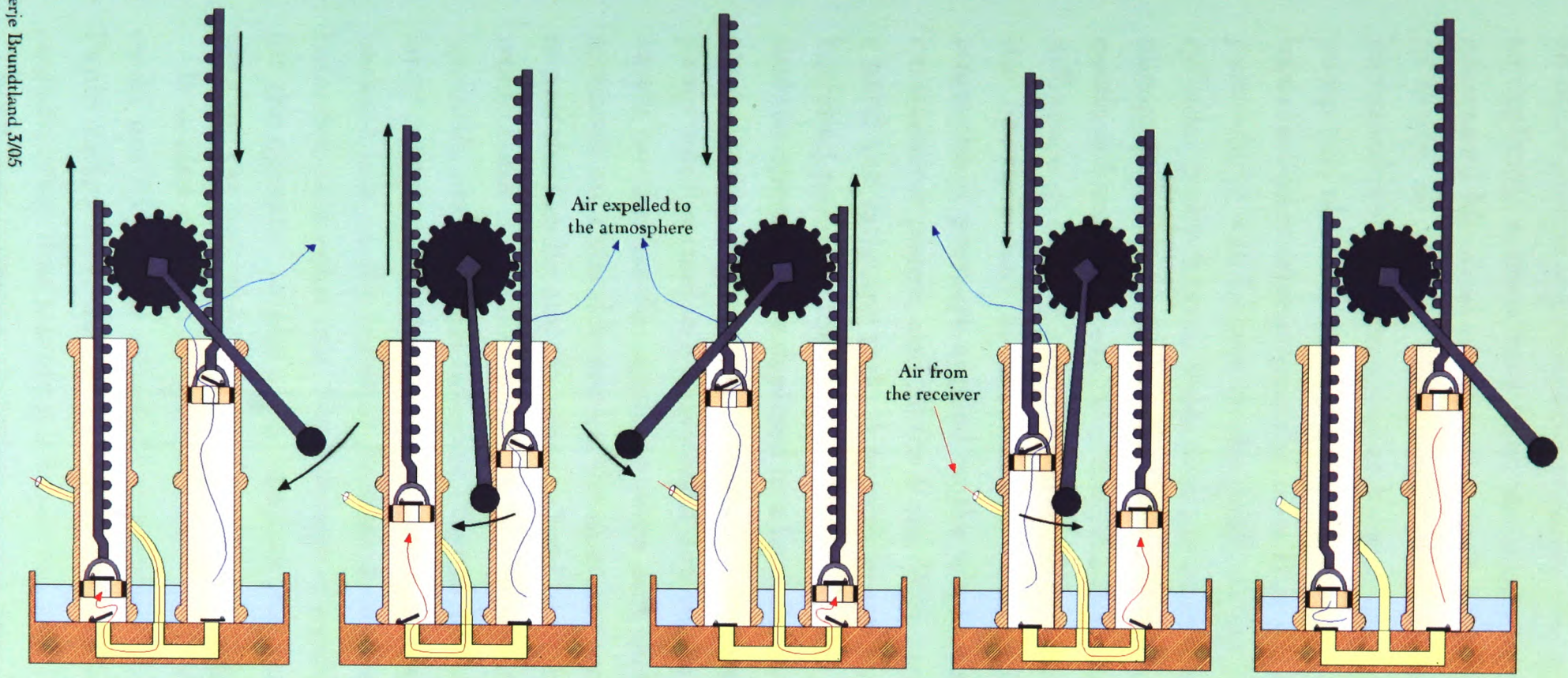



**Figure 26.** Francis Hauksbee's double-barrelled air-pump, functional diagram (March 1705). The ratio between the minimum cylinder-volume (the dead space), and the maximum cylinder-volume (right) is limiting the lowest attainable pressure. Places for potential leaks not found with the smaller pump are marked with an *l*.




**a.** Start of a pumping cycle (stroke). The crank is turned to the left and the piston in the left cylinder is pulled upwards. The bottom-valve opens due to pressure difference, and air (red) is sucked into the cylinder from the receiver.

**b.** Pumping continues. The crank is turned halfway, and air becomes sucked into the left cylinder. The bottom-valve in the right cylinder stays closed and the air (blue) is released into the atmosphere through the open piston-valve.

**c.** One half-stroke is completed and the next has started. The crank is turned to the right and the left piston is moved downwards, while air obtained from the receiver in the previous half-stroke is released to the atmosphere. The right piston is pulled upwards, and air from the receiver becomes sucked into the cylinder through the open bottom-valve.

**d.** Pumping continues. The crank is turned halfway back, and air becomes sucked into the right cylinder. The bottom-valve in the left cylinder stays closed and the air is released into the atmosphere through the open piston-valve.

**e.** One pumping cycle (stroke) has become completed. The crank and the pistons are back in their original positions. There is atmospheric pressure in the left cylinder, and partial vacuum in the right cylinder and in the receiver.

**Figure 27.** One pumping cycle (stroke) with Hauksbee's double-barrelled air-pump. In a new cycle, following **e**, the piston in the right cylinder would be pushed downwards by the atmospheric pressure, pulling the left piston upwards. This would continue until the pressure in the right equalled the atmosphere, and the right piston-valve opened. When the air in the left cylinder had expanded to a pressure lower than that in the receiver, the left cylinder valve would open, and the situation in **b** would occur.

It is interesting to see how Hauksbee underlined the advantages of his new pump in his advertisements and in the *Physico-Mechanical Experiments*. According to Hauksbee, the new method assured easy and convenient pumping, while the nearer all other pumps approached a vacuum, 'the greater their labour'. Without saying it so explicitly, it must have been the single-barrelled pump he had in mind when he contrasted his novel construction with older types. All such pumps, from Guericke to Boyle, as well as Hauksbee's own model, had suffered the disadvantages of increased labour as the receiver became emptied of air. Hauksbee's single-barrelled pump was no exception here. The fact that he compared his new pump with single-barrelled ones strengthens the view that Papin's double-barrelled engine was not particularly well-known to the public at the time. When the pumping with a one-cylinder pump began, there was air of atmospheric pressure on each side of the piston, and little strength was needed to pull the piston outwards. But as pumping continued and the pressure in both the barrel and receiver diminished, the pressure difference over the piston increased. When the minimum pressure was approached, the operator had to overcome a substantial force, in practice equal to the atmospheric pressure applied on the whole piston-area, which is about 7 kg for a 3 cm diameter piston, and 20 for 5 cm. With larger pump-barrels, pumping could be a hard and fatiguing task. A typical situation, with two men working on a single-barrelled pump, is found in an illustration by Guericke. See Figure 28 a. The fact that the operators are depicted in a backwards-leaning position is no accident, but a good picture of the actual situation. Likewise, when Hauksbee's single-barrelled pump was fastened to a heavy table or a window frame, the operator could use both hands on the handle, applying arms and body to pull it outwards. When it was mounted on a stand however, the operator would normally have needed one hand to pull the handle and the other to hold back the pump-stand; since the air-pressure would resist the pulling and the whole pump-structure would be drawn towards the operator, and perhaps fall over (Figure 16a). The advantage here of Hauksbee's latest pump was therefore considerable, the labour required to operate that pump became less as the receiver became evacuated, since the forces on each piston balanced each other out. Even though it would have been natural and comfortable for the operator to place one hand on that pump, for example to prevent it from shaking, the only force required was to operate the crank.

It is also possible to question the 'ease' of Papin's double-barrelled pump. It could not have been especially convenient to use. The operator, or 'exerciser' as Papin called him, had to mount the pump-structure and work in an awkward position every time pumping was needed. See Figure 28b.

With less fatiguing pumping, it was possible for the operator of Hauksbee's double-barrelled pump to sustain a higher rate of strokes per time-unit during the pump-down period, a fact that leads us to another important concept about air-pumps, the 'pumping speed'.

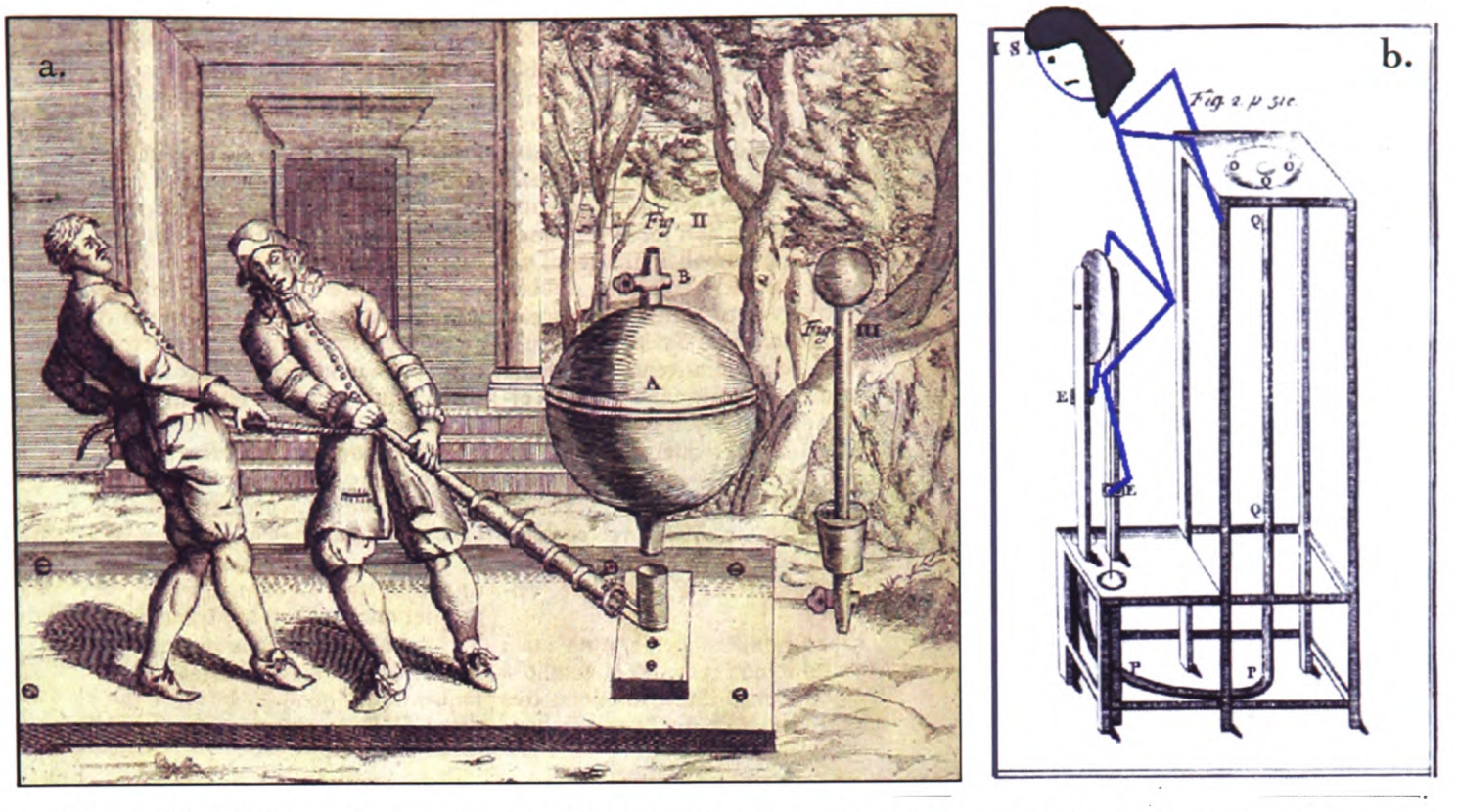



**Figure 28.** Awkward pumping positions. **a:** Otto von Guerick's second air-pump (1. Bauart, 1656). M. Puhle, *Die Welt im Leeren Raum* (München, 2002), 78, 337. **b:** Papin's 'exercise machine' (the double-barrelled air-pump) from 1676.

### 3.1.1.2 Pumping-speed

As van Helden has pointed out, in this period a short pumping-time was seen as more important than obtaining a low pressure.[255] One contribution to shortening the pumping-time had been Hauksbee's single-barrelled pumps, which gave a good vacuum in a reasonably short time. A closer examination of the matter, here called 'pumping-speed', is consequently necessary if we want to understand the functions and the importance of Hauksbee's double-barrelled model.

Before I start, however, I will introduce another concept called 'pumping-capacity'. This denotes the amount of air that can be removed from the receiver in each pumping stroke, and is dependent on the size and number of barrels. Pumping-speed is then a measure of the time needed to empty a barrel of a given size (the capacity). In general, the concept includes the time needed for the opening and closing of stopcocks as well, but are left out here since Hauksbee had made such gadgets redundant.[256] The main factor constituting a pumping-capacity is the maximum volume of the pump-cylinder(s), when the piston is moved to its outmost end.[257] This determines the volume of air that can be removed from the recipient each time the piston is pulled from its inner to its outer position. Another element is

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[255] Helden (1991), 169.

[256] See 'Experimenting pace' in Chapter 2.

[257] The concepts of pumping-capacity and pumping-speed is here based on manual driven piston-pumps only.

the 'stroke', which is the action needed for the operator to perform the pumping action and put the plunger(s) back to the start position. The pumping capacity of Hauksbee's single-cylinder pumps was approximately 250 $cm^3$ (see page 59). A pumping stroke consisted of a pull/push action of the plunger, where only the pulling operation contributed to the pumping. It is by discussing similar characteristics of the double-barrelled pump that some of the greatest advantages of this contrivance become clear.

First, the barrels themselves were bigger. Hauksbee gave the diameter to be 2 inches (approx. 5 cm), and the length to 12 (approx. 30.5 cm), equalling a volume of 620 $cm^3$. A barrel of this size was too wide for a directly-pulled single-cylinder pump, as 20 kg would have been required. But it became possible here since the operator no longer had to use so much of his physical strength to pull the piston outwards in his efforts to overcome the atmospheric pressure. A pumping stroke was made up of a back and forth movement of the crank, which caused first one cylinder, and then the other, to perform a pumping operation. This means that a back and forth movement of the crank on Hauksbee's classic air-pump had a pumping capacity of 1240 $cm^3$ per stroke. This was about 5 times more than a back-and-forth movement with the plunger could yield on his single-barrelled. But this gain must have been even higher due to the way his new pump was constructed. To operate the two interconnected barrels required much less physical labour than a single-barrelled pump, a fact that influenced the pumping-speed. On Hauksbee's single-cylinder pump, the piston-diameter was about 3 cm, demanding a pull of as much as 7 kg every time the plunger was drawn outwards. [258] The repeated, continuous pulling of a load of 7 kg for several minutes must have been rather fatiguing, so that a high pace, for example 1 stroke per second, could not have been maintained over a very long period. With a pumping capacity of 250 $cm^3$ per stroke, one stroke per second would have resulted in a pumping speed of 250 $cm^3$ per second. But with a tired operator, who for example needed 4 seconds to make a back and forth movement with the plunger, the pumping speed was only 62.5 $cm^3$ per second.[259] To increase the pumping-speed of a manual operated piston-pump is not straightforward. The capacity of the pump would increase if the diameter of the piston was made bigger, but likewise the forces that the operator had to overcome each time the plunger was pulled outward increased as well. The work would be very fatiguing, which made it impossible to maintain a high pace, and the resulting pumping speed would not necessarily be higher than with a smaller piston. If the piston diameter was kept unchanged and the cylinder length increased to achieve a bigger volume, the forces needed to pull the piston would be unaltered, but the time required for the operation would consequently be longer. The following prolonged

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[258] Chapter 1, section 1.3.1.1

[259] The only way to obtain more accurate values here is to undertake experiments with a restored pump or a replica.

pumping cycle would not increase the pumping speed in this case either. It was such physical forces that were limiting the pumping speed of such pumps.[260]

On the other hand, since the double-barrelled pump required less pain, it could be operated faster. If the operator in this case could maintain one stroke every two seconds, which was the double of the rate in the example above, a pumping speed of 620 $cm^3$ per second could be obtained. Based on the given estimates, the pumping speed of Hauksbee's double-barrelled air-pumps must have been approximately ten times higher than of his earlier, single-barrelled version.

Another concept in vacuum technology is 'conductance', which can be described as the ability of a tube to let through air. On the double-barrelled pump, the two cylinders were fastened to a perforated, horizontal 'brass piece', here called the 'lower manifold', to which a long, hollow brass-wire (tube) was connected. The other end of this tube was connected to another piece of brass, mounted under the pump plate and with communication to the receiver, the 'upper manifold'. See figure 29. During evacuation, the air was sucked out of the receiver via this tube and released to the atmosphere by the cylinders. The conductance of a tube varies greatly with the pressure but is very high in the range relevant to the air-pumps of the early eighteenth century (laminar flow).[261] Therefore, in the calculations of the required pumping time of Hauksbee's classical air-pump, the delay caused by this long tube is negligible. I have not found any indication that Hauksbee had dealt

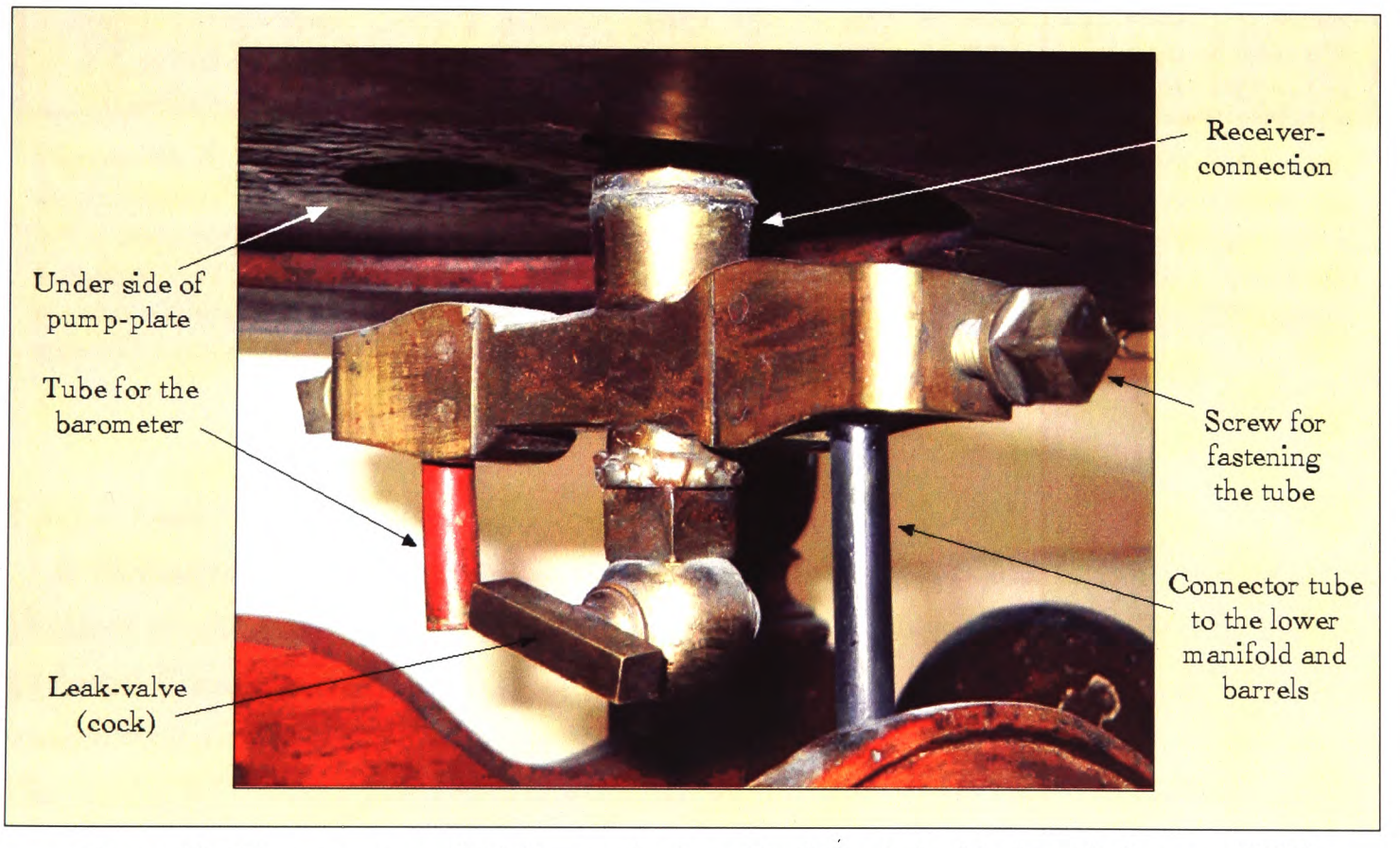



**Figure 29.** The upper manifold (brass-piece) on Hauksbee's double-barrelled pump (1705). From the Hauksbee-pump in Deutsches Museum, Munich. Photo: Terje Brundtland.

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[260] These issues were discussed by 's Gravesande in 1714. See A. v. Helden, 'Theory and practice in Air-Pump Construction', *Annals of Science* 51 (1994), 477-95.

[261] Roth, 62.

with the problem, either, presumably because he didn't experience it.

Hauksbee's contemporary, Roger Cotes of Cambridge, seems not to have been concerned about conductance either. Cotes published a textbook that included instructions on how to calculate the number of strokes needed with this particular pump to achieve a certain pressure.[262] Following his method by using the tables in Figure 30, a number of 38.4 strokes were needed to reduce the pressure in a 12.4 litre receiver (ten times the total cylinder volume) from atmospheric pressure to 1 inch of mercury, or 25 mbar. Calculations based on modern formulas yielded the same results[263]

TABLE I.

| Rarity | Number of turns | Rarity | Number of turns | Rarity | Number of turns |
|---|---|---|---|---|---|
| 1 | 0 | 60 | 5.907 | 900 | 9.814 |
| 2 | 1 | 64 | 6 | 1000 | 9.966 |
| 3 | 1.585 | 70 | 6.129 | 1024 | 10. |
| 4 | 2 | 80 | 6.322 | 2000 | 10.966 |
| 5 | 2.322 | 90 | 6.492 | 2048 | 11. |
| 6 | 2.585 | 100 | 6.644 | 3000 | 11.551 |
| 7 | 2.807 | 128 | 7 | 4000 | 11.966 |
| 8 | 3 | 200 | 7.644 | 4096 | 12. |
| 9 | 3.170 | 256 | 8 | 5000 | 12.288 |
| 10 | 3.322 | 300 | 8.229 | 6000 | 12.551 |
| 16 | 4 | 400 | 8.644 | 7000 | 12.773 |
| 20 | 4.322 | 500 | 8.966 | 8000 | 12.966 |
| 30 | 4.907 | 512 | 9 | 8192 | 13. |
| 32 | 5 | 600 | 9.229 | 9000 | 13.136 |
| 40 | 5.322 | 700 | 9.451 | 10000 | 13.288 |
| 50 | 5.644 | 800 | 9.644 | 16384 | 14. |

TABLE II.

| Capacity of the receiver | Multiplier | Capacity of the receiver | Multiplier |
|---|---|---|---|
| 1 | 1. | 60 | 41.934 |
| 2 | 1.710 | 70 | 48.866 |
| 3 | 2.409 | 80 | 55.798 |
| 4 | 3.106 | 90 | 62.729 |
| 5 | 3.802 | 100 | 69.661 |
| 6 | 4.497 | 200 | 138.976 |
| 7 | 5.191 | 300 | 208.291 |
| 8 | 5.885 | 400 | 277.605 |
| 9 | 6.579 | 500 | 346.920 |
| 10 | 7.273 | 600 | 416.235 |
| 20 | 14.207 | 700 | 485.549 |
| 30 | 21.139 | 800 | 554.864 |
| 40 | 28.071 | 900 | 624.179 |
| 50 | 35.003 | 1000 | 693.494 |

**Figure 30.** Roger Cotes's tables for calculating the numbers of strokes needed with Hauksbee's double-barrelled air-pump, to achieve a given pressure in a receiver of specified volume (ca. 1714, see note 535). A rarity of 40 times corresponds to a pressure of 25 mbar. To obtain that in a receiver with a volume ten times bigger than the barrels (12,4 litre), one has to multiply the number adjacent to 40 in Table 1: 5,322, with the number adjacent to 10 in Table 2: 7,237, which gives 37,4 pumping-strokes. From Cotes (1747), 174, 6.

### 3.1.1.3 Leak-tightening

A distinctive characteristic of Hauksbee's single-barrelled pump had been the absence of cement and sealing wax, a feature made possible by use of wet leather-gaskets. This technique had proved to be efficient and time saving, and was now transferred to the classic model. A few more details, in addition to those found in Harris (1704) were given in Hauksbee's book of 1709. Hauksbee explained, for example, that the purpose of the brass-rim on the pump-plate was to prevent shedding of the water that was needed to keep the leather moist. He emphasised

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[262] R.Cotes, *Hydrostatical and Pneumatical lectures*, edited by R. Smith (Cambridge, 1747). 173-8.

[263] $n = \frac{\ln P_n}{\ln (v_r/v_r + v_p)}$ where **n** is the number of strokes required to achieve the pressure $P_n$ in the receiver when starting from atmospheric pressure. $v_r$ is the the receiver-volume and $v_P$ the volume of the two pump barrels. Calculations based on this equation gives 38.7 strokes. See: Roth, 22.

that he always used wet leather-gaskets, and that the edges of the glasses (receiver-rims) were 'truly ground'. These features were typical for the single-barrelled pump as well, but with this engine he also described a 'dish', two inches high, in which the bottom of the two barrels were placed. The barrels were fixed through two leather collars to the lower manifold at the bottom of the dish, which would hold water, and prevent air from leaking into the barrels and the rest of the pump.

The fact that Hauksbee described the purpose of the brass rim on the pump-plate to prevent shedding of water is interesting from several points of view. This rim, and also the dish, should first and foremost be a supply of water for keeping the leather moist to prevent leaks. Without extra water, the leather would dry out during periods with vacuum in the receiver, since the absorbed water would constantly evaporate there due to the low pressure.[264] The note about the shedding of water allows a small glimpse into the experimental practice of the period. It must definitely be written from experience (Hauksbee had then used the pump for four years, 1705-9), for example, that the pump-stand would shake during pumping when the crank was moved rapidly back and forth. Also some experiments are described to 'make the whole pump shake'.[265] Water could also easily be shed if the pump was carried around in a room, for example during demonstrations.

It is also striking to see that Hauksbee contrasted the advantages of his classic pump, like the single-barrelled one, with issues typical for Boyle. This strengthens the argument that it was still Boyle's air-pump concept that most people were familiar with at the time. Hauksbee claimed that his sealing methods were 'beyond Cement whatsoever', and that experiments now could be made without 'any Daubing or Difficulty'. I have in Chapter 2 explained what the absence of sealing wax meant in practice. According to Hauksbee, since water was easier to handle than sealing wax, the entire task of performing experiments had become much more efficient.

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[264] C. Huygens and D. Papin, 'Some Experiments Touching Animals', *PT*, vol. 10 (1675), 544.

[265] See for example: W. Vream, *A description of the air-pump, according to the late Mr. Hawksbee's best and last improvements* (London, 1717), experiment no. 12.

### 3.1.2 Expedition

#### 3.1.2.1 Experimenting pace

When Hauksbee announced his double-barrelled pump in May 1705, he claimed that it could perform vacuum-experiments 'with the greatest Ease and Expedition'. I will here show that the term 'Expedition' correlates with the concept of 'experimenting pace', which I developed in the previous chapter. What lay behind this expression becomes clear in Hauksbee's book, where he asserted that it was possible to perform several experiments with his new pump 'in the same time as they could formerly make one'.[266] This confirms precisely my previous argument saying that one advantage of Hauksbee's first pump was the short time required for sealing off the receiver and easy pumping, which facilitated more experiments in a given time period.

Hauksbee gave the cause for the higher rate of experiments to be the sealing method. By using the expression 'daubing and difficulty', he signalized that it was not his earlier single-barrelled pump he had in mind, but the slow and cumbersome pumps of Boyle and Hooke. A high experimenting pace, or 'expedition' was therefore already a standard feature. It had been there with the single-barrelled pump, and also must have contributed to the early appraisals of this pump.

#### 3.1.2.2 The vent-valve

Another feature that contributed to a quicker expedition and higher experimenting pace was the possibility of letting air into the receiver in a controllable way after an experiment was over. On the single-cylinder pump, this had been facilitated by turning the pump-barrel sideways. On the double-barrelled model, however, this function was materialized as a separate, specially made gadget in the form of a valve-screw with vanes, attached to the manifold under the receiver-plate. See Figure 26 and 29. This 'Air-Cock' was an improvement over the air-inlet function of the single-barrelled pump. Previously, the maximum sideway movements of the barrel had restricted the opening of the 'valve', (the opening between the threads in the elbow), and it was never possible to open it more than a fraction of a full turn. On the double-barrelled pump, the screw could be operated without any such restriction. It could probably be screwed out and fully removed to allow a maximum influx of air, if this was found preferable.

Quick and simple sealing and a controllable air-inlet facility were two factors constituting the concept of 'Expedition'. The third element, easy and convenient pumping, was discussed above.

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[266] *PME*, 3.

### 3.1.3 Exactness

I have shown in the previous chapter that the term 'exactness' alluded to the inbuilt barometer and the air-inlet facility. The double-barrelled pump possessed similar features, but with some improvements regarding the barometer. It was not particularly mentioned in the advertisements, but was given much attention in Hauksbee's book. Hauksbee portrayed the barometer as 'another Excellency, where the degree of rarefaction in any experiment is at all time most nicely observed'. He underlined the way it was mounted, placed under the pump-plate and protected by the vertical posts, where it 'cannot receive damage, and out of the way of anything for experiments'.[267] But the most substantial upgrading from the single-barrelled pump was clearly the increased accuracy. Like the earlier model, the barometer consisted of a glass tube with the lower end submerged into a mercury-reservoir and the upper connected to the recipient, here via the manifold under the receiver plate.

At some point, Hauksbee must have become aware of a small error that occurs in barometers of this kind. Despite the many advantages compared to Boyle's arrangement, it was not perfect. The problem derived from the fact that the scale was fastened to the glass tube, and therefore had a fixed zero-point relative to the surface of the mercury in the reservoir. The actual pressure in the receiver was measured by the distance between the surface of mercury in the tank, and the upper end of the mercury column in the glass tube. But when pumping lowered the pressure in the receiver and the mercury was sucked upwards in the tube, the amount of mercury in the reservoir would decrease a little, since it contributed to filling the tube. Therefore, the mercury-surface would sink as the column rose in the tube. The distance between the two surfaces would give the actual pressure, but since the measuring rod was fixed, its zero-point would not be at the same level as the lower mercury surface when the mercury column was high. Reading the pressure by comparing the upper end of the column with the graded scale would therefore not produce a fully correct measurement, and the error would increase when the pressure became lower (a higher mercury column). This means for example that it would never be possible to obtain a reading that showed a fully exhausted receiver. The error in such systems is proportional to the square of the ratio between the internal diameters of the tube and the reservoir.[268] A tube with a 0.2-inch (0.5 cm) bore and a reservoir with an internal diameter of 2 inches (5 cm) would give a factor of 1/100, or 1%. Applying these numbers on Hauksbee's first air-pump (Figure 6 and 21), every reading would be 1% too low. This would cause up to 0.75 cm difference in mercury-height at low pressures. If the air in the receiver had been diluted 40 times, equalling a pressure of 25 mBar, the barometer would show about 35 mBar, indicating a reduction of only 28 times.[269] The only

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[267] Ibid.
[268] See: Middleton (1964), 117.
[269] (Normal atmospheric pressure is approximately 1000 mBar; 760 mm Hg; or 29,5 inch Hg).

way to obtain a correct reading was to loosen the measuring rod and slide it downwards until its lower mark reached a distinct height above the mercury-surface. Adjusting the index for every new measurement could not have been very convenient, and carried the risk of breaking the fragile barometer-tube.

It is reasonable to think that this error must have challenged Hauksbee's claim that his pump allowed the performance of experiments with ease, exactness and expedition. From the *Physico-Mechanical Experiments,* we know that Hauksbee had managed to solve the problem. On the double-barrelled pump, he had attached the index-rod to the barometer tube by small metal loops, so that it could slide freely up and down. The rod was resting on a piece of cork that was floating upon the mercury in the reservoir, and would therefore move up and down as the surface rose or fell. The distance between the mercury surface in the tank and the top of the column would always be measured correctly, since the zero-point of the scale was 'locked' to the lower surface. The difference between the two systems can be noticed by comparing the mercury-reservoirs of the two pumps. The top of the mercury-tank was covered on the single-barrelled pump and open on the other, to allow free movements of the cork and the measuring-rod. See Figures 5, *m-m*, and Figure 6. A schematic diagram is given in Figure 31. No other authors have previously commented on this smart contrivance by Hauksbee. In a classical study of such instruments, *The History of the Barometer* by Knowles Middleton (1964), the idea of applying a floating index to keep the mercury surface at the zero-point was first suggested the 1770s.[270]

Hauksbee also introduced another remedy for making more accurate measurements. In addition to the 'self calibrating' scale, the scale itself was supplied with a finer graduation than its predecessor. The graduation of the scale on the first pump had been in half-inches.[271] On this model, he had marked each quarter of an inch from the surface of the quicksilver to a height of 28 inches. Above that, it was graduated in tenths of an inch.[272]

Hauksbee's efforts to increase the barometer accuracy suggest that he had made extensive use of the single-barrelled pump, since such incompletenesses normally becomes clear during practice. It is also from practice that ideas of how to solve such problems often arise. The finely-graduated, floating index shows that Hauksbee had a special interest in observing the mercury at its ultimate level, which means that the lowest attainable pressure had become an issue.

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[270] Middleton (1964), 203.
[271] Obtained from a close examination of the image in Figure 6).
[272] In modern terms, pressure equivalent to a tenth of an inch of mercury is approximately 2.5 mBar.

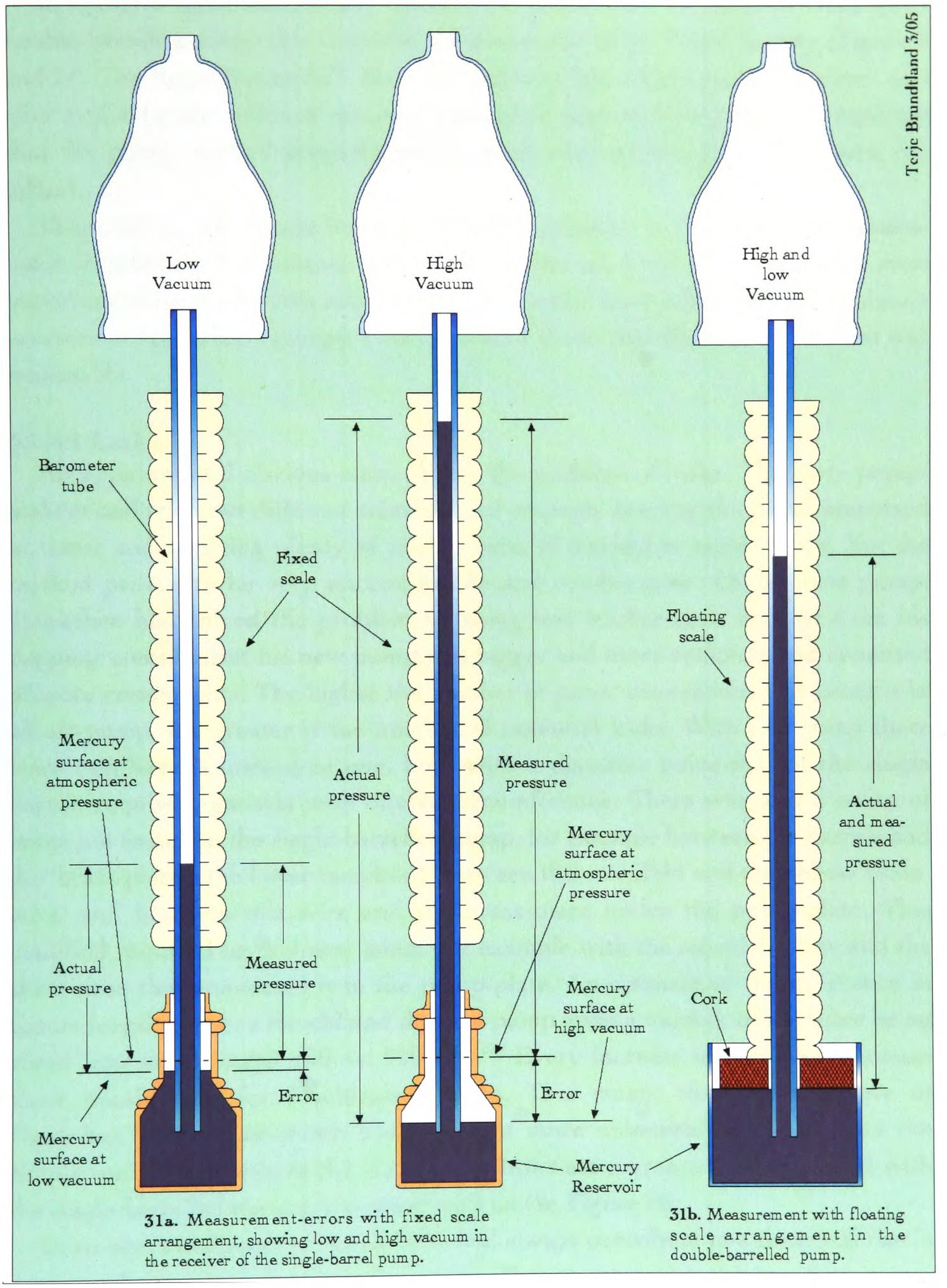



**Figure 31 a and b.** Accuracy of the different barometer-scale arrangements. Principle drawing.

### 3.1.4 Lowest attainable pressure

In 1926, the instrument-maker Robert Paul restored the exemplar of Hauksbee's double-barrelled pump that is now in the possession of the Royal Society (Figure 5 and 24, 'The Royal Society').[273] He described it as 'beautifully made in walnut', and after replacing the deficient receiver, barometer tube, and leathers, Paul reported that the pump worked properly and gave an end-vacuum of about 1 inch (25 mBar).

There are several factors limiting the lowest pressure in this kind of air-pumps, but it is uncertain if Hauksbee was aware of them all. I will here discuss the most important of these elements and see how they would have influenced the minimum pressure in Hauksbee's pumps, a survey which shows that Robert Paul's result was reasonable.

#### 3.1.4.1 Leaks

An apparent and obvious element was the problem of leaks. The early pump-makers had tried out different solutions, for example keeping the pump immersed in water and applying plenty of sealing wax. It worked to some extent, but the method proved to be very uncomfortable and cumbersome. On his first pump, Hauksbee had solved the problem by using wet leather-seals derived from his cupping utensils. But his new pump was bigger and more complex, and consisted of more components. The higher the number of parts, connections and joints is in an air-pump, the greater is the number of potential leaks. With this pump there were two barrels instead of one, both with a diameter twice that of the single barrel, requiring gaskets with double circumference. There was also a series of joints not found on the single-barrelled pump, for example between the barrels and the 'brass-piece' (the lower manifold), between this manifold and the hollow brass-wire, and between this wire and the brass-piece under the pump-plate. This manifold required several new joints, for example with the air-inlet screw and the short tube that connected it to the pump-plate. An estimate of the difference in fissure length between the old and the new pump gives a number of the latter being about four times longer (30 vs. 120 cm).[274] Every increase in this length creates more possibilities for troublesome leaks. This meant that the structure of Hauksbee's classic air-pump itself made it more vulnerable to leaks than the simpler one. Places where the chances for leaks are increased, or not found with the single-barrelled pump are marked with an *l* in Figure 26.

In an evacuated receiver, small leaks will always contribute to a continual rise in pressure due to the constant influx of air. The way to tackle this is, of course, to pump it away. The minimum pressure in an air-pump is reached and maintained

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[273] E. N, Andrade, 'A Lecture with Experiments on Various Subjects', *Journal of Scientific Instruments*, vol. IV. 5 (Feb. 1927), 137.

[274] Especially the longer fissures on the two, larger barrels and on the upper and lower manifolds contributed to this.

when the pumping speed (the rate of removal of air) is equal to the influx of air through the leaks, plus the evaporation from components inside the pump itself. In practice, after a receiver had been evacuated and an experiment was in progress, the operator had to make some strokes with the crank from time to time to keep the pressure at the intended level.

The double-barrelled pump had a higher pumping speed, but more possibilities for leaks than the single-barrelled one, which raises questions about its superiority. This issue will be discussed later in the chapter.

### 3.1.4.2 The dead space

A constructional detail that limited the pressure in Hauksbee's air-pumps was the space that remained between the piston and the bottom of the cylinder, when the piston was pushed to its lower end. The size of this cavity, called the 'dead space', was determined by the geometry of the cylinders and the design of the valves, and the designers tried always to make it as small as possible. It could not be eliminated fully, however, since some space was required for free movements of the leather-flaps.[275]

When the piston was forced downwards, the piston-valve would open and let out the air in the cylinder. It would stay open till the piston had reached the bottom, causing the small cavity below the piston to be filled with atmospheric air. This air would expand and fill the barrel when the plunger was pulled outwards, and only when it had been diluted to a pressure lower than that in the receiver would the bottom-valve open. Air from the receiver would flow into the barrel and become further diluted, but only the rest of the pumping stroke would contribute to this. The pressure in the receiver could never be lower than the pressure in the barrel, and this pressure could never be lower than the pressure from the atmospheric air in the dead space when this had expanded into the whole barrel.

The final pressure in the receiver was therefore dependent on the relationship between the dead space and the total volume of the barrel (see Figure 26). Hauksbee did not mention this problem explicitly but the corresponding issue with condensing pumps, where the problem is about the maximum pressure that can be obtained in a closed container, was thoroughly discussed in an article in the *Philosophical Transactions*.[276]

At some occasions, Hauksbee had water in the barrels to obtain a better sealing. If this was the case, it would contribute to fill the dead space and make it smaller. On the double-barrel pump, each barrel had a volume of ca. 620 $cm^3$. If we estimate the dead space to be 5 $cm^3$, the minimum pressure that could be obtained in the receiver would be about 8 mBar, corresponding to 1/4" of mercury.[277] With

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[275] John Smeaton tried to get around the problem by a totally new construction. See: 'A letter from Mr. J. Smeaton, to Mr. John Ellicott, FRS, concerning some improvements, made by himself in the air-pump', *PT*, vol. 47 (1753), 415-27.

[276] F. Hauksbee, An account of an Experiment, *PT*, vol. 24 (1705), 1902-4.

[277] Roth, 203.

the given relationship between the dead space and barrel volume, the pressure in the receiver could not under any circumstances be lower than this. With smaller pumps, the ratio between the dead space and the cylinder was not necessarily much different. If the single-barrelled pump had a dead space of 2.5 $cm^3$, the final pressure could not be lower than 10 mbar.

### 3.1.4.3 Valve equilibrium

There are other limiting factors as well. An important feature with Hauksbee's pumps was the absence of stopcocks, which made it superior to older models. But Hauksbee's solution, replacing manual stopcocks with automatic valves, had disadvantages too. The valve in the bottom of the barrel was designed to open and close due to pressure difference over the flap, which was no problem in the beginning of a pumping task. The pressure on one side of the flap would have been much greater than on the other, and sufficient to force it open. But as pumping diminished the pressure in the receiver, the pressure difference over the flap was reduced. Some force was always required to overcome the tension in the valve-material that kept it closed. At some point, the pressure difference would be too small lift up the flap and the valve would stay closed, and no further pumping would be possible (valve equilibrium). The challenge was to prepare and apply the right sort of material, which gave both optimal tightening and was as easy to lift up as possible, an issue I discussed with the cupping utensils.

The lowest attainable pressure in this kind of pump would therefore be limited by the ratio between the volume of the dead space and the total cylinder volume, *plus* the force required to open the bottom-valve. If the minimum pressure in the cylinder was 8 mBar due to the dead space, and the minimum pressure needed to open the valve was 4 mbar, a pressure of 12 mBar in the receiver was the best the operator could hope for.

The problem of valve equilibrium in air-pumps had been known since Guericke's period, but was not regarded as especially relevant since most pumps prior to Hauksbee had stopcocks. In 1714, Musschenbroek discussed the problem but chose to use stopcocks that opened and closed automatically, synchronized with movements of the piston. The conclusion by modern commentators so far is that although the problem was known by the air-pump makers of the period, it might not have been fully recognized.[278]

Hauksbee's attitude to the problem has never been examined. A survey would be helpful for gaining better insight into his engagement and general understanding of pneumatics. There are no indications in Hauksbee's articles or book, nor in the papers in the Royal Society, saying that he was concerned about the issue. But again the newspapers give a hint. From an advertisement of January 1714 by Hauksbee's wife Mary, it becomes clear that he definitely had been aware of the problem. Soon after Hauksbee's death in April 1713, Mary continued the public

[278] Helden (1991), 167.

lectures that he and Desaguliers had given in London since 1712, and continued to sell his instruments as well. During his last years, Hauksbee had started to feel competition from his nephew, Francis Hauksbee the younger. Now, after his death, his wife put up an advertisement trying to convince the public that the air-pumps of her late husband were superior to those of his younger nephew:[279]

> N.B. Wheras other Air pumps exhaust the Receivers by the Airs lifting up Valves, these pumps, not having that Inconveniency, are more valuable than any yet made, upon a contrivance in the piston that gives the Air free passage at each Exhaustion. This new improvement, which the late Mr. Hauksbee made a little before he died, was communicated to no other Workmen beside Richard Bridger aforsaid, who now makes all the pumps with it. [280]

From this it follows that Hauksbee's solution of the valve equilibrium-problem had been kept secret. It sounds like it was a mechanism connected to, or activated by, the pistons, but I have not been able to find anything specific about it in the contemporary literature. Hauksbee junior, who answered his aunt in an advert two weeks later and said that he also knew that particular secret,[281] has not left any information about these gadgets either.[282] No indications of any special mechanism for this purpose were found from a limited survey of the surviving Hauksbee-pumps. Until an extensive study of these pumps is undertaken, the question about what the secret consisted of must be left open.

What is important, however, is that Hauksbee was aware of the problem of valve equilibrium, and tried to do something about it. He must have realised that his pumps could not evacuate the receiver to more than a distinct level, and might have thought of the shortcoming of the valves as a probable reason.

### 3.1.4.4 Vapour pressure

There is one issue concerning the lowest attainable pressure in air-pumps that neither Hauksbee nor his contemporaries seem to have been aware of, namely 'vapour pressure'. I will in the following show that it must have been this phenomenon, and not the dead space or the stiffness of the valve-flaps, that in the end limited the vacuum.

Saturated vapour pressure is defined as the pressure exerted by a vapour in contact with its liquid form, for example water vapour that evaporates from water inside a closed container.[283] Boiling takes place at the temperature where the vapour pressure equals the surrounding pressure, which is 100°C at sea level. At higher altitudes, water boils at lower temperature since the atmospheric pressure is

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[279] Morton and Wess interpret this as a family controversy. See: Morton and Wess (1993), 50.
[280] *The Englishman*, 7 Jan (1714), and *The Daily Courant*, Jan 9 (1714).
[281] *The Englishman*, 21 Jan (1714).
[282] Nothing was found in F. Hauksbee [Junior] and W. Whiston, *A Course of Mechanical, Optical, Hydrostatical and Pneumatical Experiments* (London, Undated,). [The book is undated, but a publishing date of March 1714 can be set from the Newspaper-advertisements].
[283] P. Walker (ed.), *Chambers Science and Technology Dictionary* (Edinburgh, 1992), 944.

reduced. In an air-pump receiver, where the pressure is reduced considerably, water can boil at room temperature.[284] Water was crucial for keeping Hauksbee's pump from leaking, and there must always have been some of it inside the receiver and in the barrels. During evacuation at a temperature of 20°C, this water would start to boil at about 23 mBar, filling the receiver with water vapour. As long as there were water particles in the pump, for example in the inner part of the leather gasket under the receiver, the final pressure could never be lower than that exerted by this vapour. This means that when Hauksbee and his contemporaries tried to obtain a good vacuum by prolonged pumping, the water, in other respects a valuable element, would start to boil and give off vapour when the pressure was reduced to 23 mBar. At room temperature, this pressure would be maintained by a continuous evaporation of water, and further pumping would be fruitless. It is this effect that determines the lowest attainable pressure in water-sealed air-pumps, limiting it to 23mBar. Attempts to remove the vapour by extended pumping would in the end only cause the seals to dry up, resulting in leaks.

The lowest attainable pressure in air-pumps of this kind is governed by a series of factors. Leaks, dead spaces, valve-equilibrium, and evaporations from various materials inside the receiver would all make up the lower limit for the vacuum. The dead space combined with valve resistance would set the ultimate pressure to about 12 mbar. But it was the vapour from the crucial sealing agent – water – that paradoxically constituted the limitations of Hauksbee's pumps, giving a theoretical end-pressure of about 23 mbar. In practice it would have been even higher than this, due to minor leaks and other imperfections. The value obtained by Robert Paul of about 1 inch of mercury or 25 mbar in the restored pump correlates well with the discussion above.

Vapour pressure as a barrier for a low vacuum seems not to have been fully understood before the second half of the eighteenth century.[285] There are no signs that Hauksbee was aware or thought of it, but he definitely made great efforts to eliminate the other obstacles.

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[284] Roth, 19.

[285] A good description of the growing attention to this phenomenon is found in: Ch. Hutton, *A Mathematical and Philosophical Dictionary* (2 vols, London, 1796), i, 56-7.

### 3.1.5 State of the art.

Francis Hauksbee's double-barrelled air-pumps from 1705 is a masterpiece and represents the 'State of the Art' in pneumatics of the period. Many have speculated about Hauksbee's background, and wondered how he came to build such a beautiful instrument.

The similarities between his and Papin's double-barrelled pumps are in many senses striking, a fact that has made modern commentators see Hauksbee's pump as just an improvement of Papin's. The shape of the pump-structure itself, the interconnected barrels, and the self-closing valves all resemble the corresponding elements and functions of Papin's pump. We do not know when Hauksbee first learned about this pump, and as I showed in the previous chapter, it seems not to have been so well-known in the period as modern historians have thought. Hauksbee could possibly have learned about it from the *Lexicon Technicum,* of which he owned a copy. The idea of using two interconnected barrels could then have been taken from Papin's pump and the gearwheel and rack arrangement from Boyle's, since both pumps are described and depicted there. I see it more likely that he had learned about these issues earlier, but will argue that the valves that Hauksbee applied could not simply have been copied from Papin's. First, the use of self-closing valves in pumps was not new for either Papin or Hauksbee. This principle had been used for water-pumps since antiquity, and a system of two interconnected barrels with self-closing valves in the pistons had, for example, been described and depicted by Agnostino Ramelli in 1588.[286] This principle must have been well-known at the time, and could have inspired Papin to make a similar valve-system for air.

Regarding Hauksbee, however, we know that he arrived at a similar solution by quite a different route. I have in Chapter 1 described the development and the importance of his valves for cupping utensils and anatomical instruments, and showed that this knowledge was transferred to his first air-pump. Hauksbee's ingenuity on this point was that he managed to make tiny and reliable valves for air for use in commercial products, which is much more difficult than to make coarse closing mechanisms for water. In the first case even small leaks can be fatal, 'destroying' the vacuum, while with water-pumps, which normally transport the medium from one place to another, some spill can be tolerated. The medium, water, will also act as a sealing agent itself in such pumps, but in air-pumps where the intention is to remove the air totally, the medium has no such function.

Questions about Hauksbee's background have been addressed many times. The most common assumptions are that he had earlier worked as an assistant for Boyle or Papin, which are used to explain his knowledge of pneumatics and his ability to make the double-barrelled pump. It is sometimes said that his first experiments in the Royal Society 'echoed' those of Boyle, and that his pump in principle was just

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[286] Agostino Ramelli, Le diverse et artificiose machine (Paris, 1588). English translation: *The various and ingenious machines* (New York, 1976), 158-9.

an improvement of Papin's. Although a connection between Boyle and Hauksbee was first put forth as a careful suggestion only by Guerlac in the 1950s, it has been repeated over and over again since, and now has become a matter of fact. One example on this is found in *A Dictionary of Scientists* by Oxford University Press (1999), where Hauksbee is portrayed as an English physicist and a student of Boyle.[287] So far I have found no evidence that supports this. A former relationship between Boyle and Hauksbee cannot be ruled out, and it is obvious that he must have known about Papin's pump before he built his own double-barrelled one. However, I have argued that without the experiences that he gained from making cupping-utensils, especially the reliable valves, he would never have been able to develop the air-pump to the level that he did.

I will therefore conclude that even though we find elements from both Boyle and Papin's pumps in Hauksbee's double-barrelled masterpiece, all the important details like the self-acting valves, sealing methods, and pressure measurements were transferred from the single-barrelled model. Some of these functions were improved, like the increased pumping speed and barometer accuracy, while others, such as leak problems and the lowest attainable pressure, were more or less unchanged, or even could have been worsened.

## 3. 2 The two pumps

The fact that Hauksbee made and used a smaller air-pump for several years before the double-barrelled one was introduced opens up new and interesting perspectives. From the status and popularity which Hauksbee's double-barrelled pump has achieved in the secondary literature, it feels obvious that the introduction and incorporation of it should have been well-described in contemporary writings. But the opposite is the case; evidence of the new pump is in fact scarce. Why?

A discussion of these issues is important, because it will tell us much about the state of the air-pump in this period, as well as about Hauksbee as an instrument-maker, lecturer and demonstrator. Technical, scientific, economic, and social issues must have played a role in the development, incorporation and documentation of this pump. I will here discuss technical and scientific matters of this issue, the social aspects will be handled in Chapter 5.

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[287] J. Daintith and D. Gjertsen (eds.), *A Dictionary of Scientists* (Oxford, 1999).

### 3.2.1 The evidence

Some information that sheds light on these matters can be obtained by examining the *place* and the *form* of the evidence that can now be found. A natural starting point when looking for signs of more than one Hauksbee-pump is his series of articles in the *Philosophical Transactions*. These articles represent a continuous series of accounts of his experiments from April 1704 to December 1713.[288] One feature that makes them particularly useful is that several of the articles were published before the double-barrelled pump was made. A study of these articles, from the beginning to some time after the double-barrelled pump was introduced, reveals that the texts contain hints about, for example, receiver-volume, pumping time and other technical issues. This information makes it possible to 'reconstruct' the capacity of the actual pumps in use, which again can be used to distinguish between the different models.

One example is an experiment performed in the Royal Society on 20 December 1704, where Hauksbee demonstrated the effects of firing gunpowder in vacuum. The tests were performed in a specially-made receiver containing a mechanism for dropping equal amounts of gunpowder onto a red-hot iron block.[289] Hauksbee gave the pumping time as two minutes, and the volume as equal to 25.5 ounces of water, corresponding to 725 $cm^3$.[290] However, in a series of experiments described ten months later, he operated with receivers of quite different proportions.[291] While investigating the phenomenon of mercurial phosphorus, he produced luminescence by letting mercury droplets hit a rounded glass-surface inside an evacuated glass-cylinder with rounded top. Only the height was given (21 inches, or 53 cm), but the diameter can be approximated to about 6 inches (15 cm) from the illustration. Estimating a wall thickness of 0.5 cm, this provides a volume of about 8000 $cm^3$, or 8 litres. The given pumping time for this particular experiment was two minutes as well. Since the pumping times, which must have been approximate values only, were the same in both cases, while the receiver volumes were different, these examples suggest two different pumps. The difference in receiver volumes was about 11 times, which is of the same magnitude as the relationship between the estimated pumping speeds of the single and double-barrelled pumps, 10.5 times (62 and 650 $cm^3$/second). The single-barrelled pump must therefore have been used for the gunpowder experiment, and the double-barrelled one for the investigations of mercurial phosphorous. A sketch showing the two receivers depicted to the same scale is given in Figure 32. The chafing experiment published in December 1705 must also have been performed with the smaller pump, since the illustration showed the single-barrelled pump stand (Figure 16a).

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[288] Three articles were published posthumously.
[289] F. Hauksbee, 'An Experiment Made at a Meeting of the R. Society', *PT*, vol. 24 (1705), 1806-7.
[290] See Chapter 4.
[291] F. Hauksbee, 'Several Experiments on the Mercurial Phosphorus', *PT*, vol. 24 (1705), 2129-35.

I have also looked for clues of different pumps from the way air was let into the receiver when a pressure-change was required. In one experiment, conducted at least twice in the Royal Society, (8th, and 25th March 1704), Hauksbee demonstrated the effects of rarefied air on sound. By activating the clapper of a bell inside a receiver by shaking the pump, he was able to show that sound diminishes under reduced air-pressure. When air was let into the receiver again and the shaking was repeated, the intensity increased. Hauksbee recounted that air was given access into the pump in steps: 'not by once, but by turns'.[292] This is however close to the expression that Harris used when he described this deliberate leak function on Hauksbee's single-barrelled pump. According to him, the operator could let air 'easily insinuate itself between the Joints of the Screw', by '*turning* the Air Pump about from Left-hand towards the Right'. Therefore, Hauksbee must have performed these experiments with the single-barrelled pump. Moreover, in an experiment performed some time before October 1705 about the effect that various degrees of vacuum had on barometric light, he said he 'suffered air to re-enter the receiver by the Cock'. This is a clear indication that the double-barrelled pump must have been used, since this was equipped with such a device.

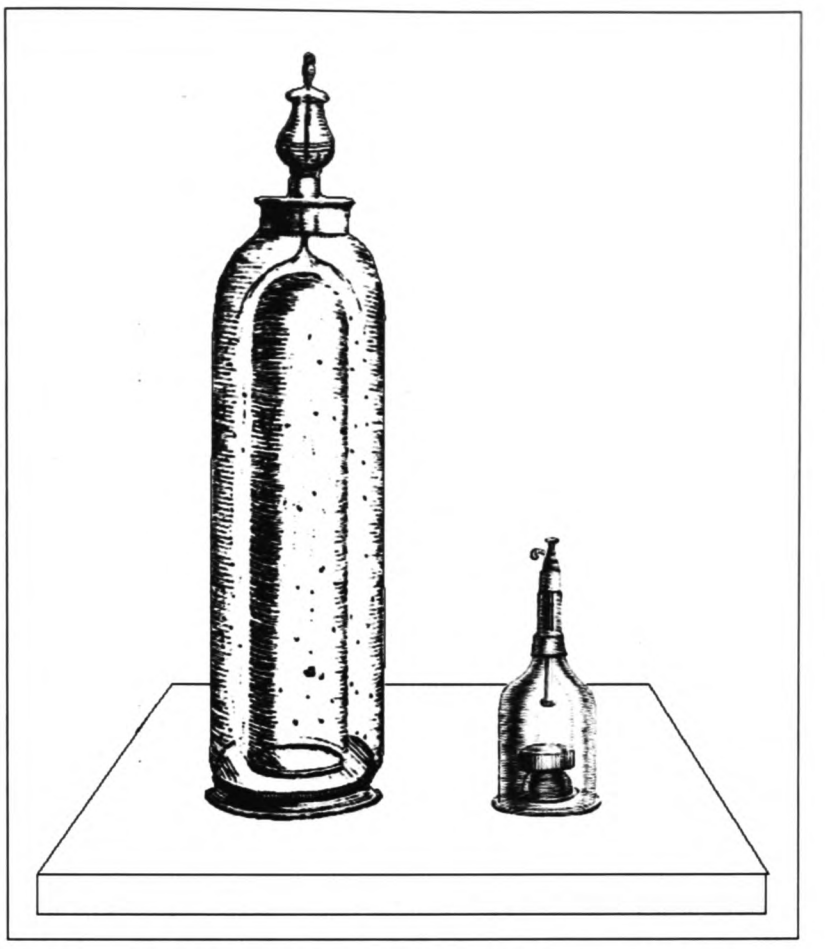


**Figure 32.** Apparatus for the Mercury (left) and the Gunpowder experiments, drawn to the same scale. The volume of the mercury-glass was given as 0.725 litre, and the gunpowder-glass was calculated to 8.0 litre. According to Hauksbee, both required the same evacuation time, two minutes.

Another relevant source is the 'Journal Book' of the Royal Society, which contains minutes of the weekly meetings of the period. Hauksbee's name figures rather often in these notes, but even after a close reading, nothing could be found explicitly about the double-barrelled air-pump. In fact, the word 'pump' is rarely mentioned, even though we find many notes about experiments in a vacuum. For example, in 1705, the year when the double-barrelled pump was introduced, no reference to any air-pump was found at all. In fact, in the period from June 1704 to March 1707, air-pumps are only referred to once, on 22 May 1706.[293] At a meeting that day, Hans Sloane gave an account of a new way to make a pneumatic engine,

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[292] F. Hauksbee, 'An Account of an Experiment Made at a Meeting of the Royal Society at Gresham College', *PT*, vol. 24 (1705), 1904.

[293] The Royal Society, 'The Journal Book', JBC 10 (London, 1702-1714), 22 May, 1705.

contrived by Musschenbroek in Leiden. It is unclear which of Musschenbroek's pumps was presented here. According to Peter de Clercq, the discussion could have been based in theory on prints and illustrations of either a horizontal air-pump, first published in 1694, or a Senguerd-type pump that had been on the market for decades, but with no illustration available before now (1706).[294] But if this was the case, argues de Clercq, why should such a learned and experienced body as the Royal Society treat this as an account of a novel way of making a pneumatic engine? One solution is that it was, for us, an unknown air-pump by Johan Musschenbroek that was presented, a possibility that has some support in the sources. What makes this discussion so interesting here, however, is that the fellows compared the Dutch engine with Francis Hauksbee's latest contrivance. For de Clercq, this fact supports the supposition that the presented Musschenbroek pump could have been something special and new, since it was compared to a pump that had been around for several years. He assumes of course that Hauksbee's double-barrelled pump had been in use at least from December 1703. But I see another possible interpretation here. According to the text, Musschenbroek's concept 'was thought to be inferior of the late way of Mr. Hawksbee'. The Dutch pump might have been of a novel construction, or it might not; what really stirred the interest among the fellows that day was the possibility of contrasting Hauksbee's new double-barrelled pump to a continental model. The wording 'the late way' suggests that Hauksbee had rather recently come up with a new model, and now they had the opportunity to evaluate it in a broader perspective. At this stage they must have been well-acquainted with the single-barrelled pump, but would also have been familiar with the double-barrelled model. Their conclusion was clear: the Musschenbroek type was not as good as Hauksbee's double-barrelled pump.[295]

It also becomes clear that after hearing the discussion about the Musschenbroek pump versus the Hauksbee pump, Hauksbee himself 'was desired to give a Description of the Air-pumps invented by him'. Such an account was not given until three years later, in his book *Physico-Mechanical Experiments* from 1709. This book is a third source of information on Hauksbee's activities with air-pumps. It has been pointed out that much of the content consists of more or less edited versions of his earlier articles in the *Philosophical Transactions*.[296] An important addition, however, is the detailed description of the double-barrelled pump that is found in the beginning of the book. This account is accompanied by two images of the pump. In one it is depicted as part of the chafing experiment, now replacing the single-barrelled pump-stand in the *Philosophical Transactions* of December 1705 (Figure 5 and 16 b). However, in the *Physico-Mechanical Experiments* there are even

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[294] de Clercq (1997). 'An Air-pump puzzle', Appendix M, 257.

[295] A similar judgement was given to a microscope by Musschenbroek, which they thought was inferior to one by Mr. Wilson.

[296] Roller (1970), xvii.

fewer hints of a pump prior to the one described than in the original articles. The experiment with gunpowder, for example, which must have been performed with a single-barrelled pump, is not described in the book at all.

The lecture advertisements represent another field of Hauksbee's activities, but not much was found there either when I searched for evidence about different air-pumps. In the first series of announcements, from December 1704 and January 1705, the text describes the pump as: 'There is provided Engines for Rarefying and Condensing Air'. This wording might suggest that the author had the single-barrelled pump and the compression syringe, or possibly the combined engine, in mind. But the same phrase was repeated in later advertisements as well, after the double-barrelled pump had become available. Therefore, from these advertisements, nothing conclusive can be said about an introduction of a new pump.

A fifth source is Hauksbee's sales advertisements: they are much richer on technical matters than those above, giving valuable information about his various instruments, for example his air-pumps. The time of their introduction is also significant. It is from these advertisements, which have previously not been consulted by modern commentators, that we know that Hauksbee's double barrel-pump became available on the market in May 1705.

## 3.2.2 Technical and scientific matters

### 3.2.2.1 One versus two

The survey above shows that there is some evidence, though not much, of multiple pumps in Hauksbee's writings. We understand that he used a single-barrelled pump for the gunpowder experiments in December 1704. About a year later, in October 1705, he used a double-barrelled one in a series of experiments concerning mercurial phosphorus; and in December that year, he published an article accompanied with an illustration of a pump-stand for a single-barrelled pump (The chafing experiment). Next year, in May 1706, the fellows of the Royal Society discussed a Musschenbroek-pump, which was assessed as inferior to Hauksbee's latest version, which must have been the double-barrelled model. Based on these reports, we can say that Hauksbee must have introduced the new, bigger pump sometime in 1705, and incorporated it in his experiments during 1705 and 1706, while the smaller one was still in use. This conclusion correlates well with our knowledge of Hauksbee's first announcement of the double-barrelled pump, which was in May 1705, but it also raises several important questions.

For an instrument-maker who manufactured medical and philosophical instruments for sale, it must have been natural to announce the new, double-barrelled air-pump in the newspapers. To us, an immediate consideration is that it must have been just as important to make the new contrivance known in his

lectures and demonstrations, as well as in the experimental accounts. But this seems, however, not to be the case. The fact that the introduction of Hauksbee's double-barrelled air-pumps is not explicitly mentioned in his own experimental accounts, as well as in his employers, must mean something. For example, the known evidence about different engines is all written in a casual way. The style is informal, and the place seems to have been chosen more or less at random, only extractable by a close, focused reading of the texts. And we never find notes like 'these experiments were made in my new double-barrelled air-pump', or 'Hauksbee demonstrated his new double-barrelled air-pump', etc. The form and place of the available information shows that there were definitely no intentions to inform the readers about the kind of pump in use. When the description of the double-barrelled model was finally given in his book of 1709, it came as an independent and separate, freestanding chapter, placed in front of the rest of the text. The new pump was a masterpiece and state of the art for its period, and it is not for nothing that it has come down to us as the symbol of Hauksbee's ingenuity and skill. But why was he not trumpeting the presentation of the new pump more loudly? There exist no similar assessments of the double-barrelled pump as those by Harris, Derham and Hodgson addressed to the single-barrelled model. Why do we not find any particular appraisal of it in the 'Journal Book' or the other sources? Contrasted to the popular belief of Hauksbee's classic pump as a major breakthrough in air-pump technology of the early eighteenth century, these are all natural questions to ask.

So why was the introduction of the double-barrelled pump apparently so smooth? I see several possible answers here. One explanation is that Hauksbee regarded his double-barrelled air-pump as so much better than his first model that the earlier one simply became not worth mentioning at all. The fact that Hauksbee never published a proper description of the single-cylinder pump himself, or gave any illustration of it supports this view. So does the prominent place that the classic pump was given in the opening section of his book, accompanied with two detailed illustrations. Also the bare appearance of this pump itself, made from brass, glass and walnut, and its beautiful woodcarvings make it likely that this is something a professional craftsman would have wanted to be associated with and remembered by. It is therefore not unlikely that when Hauksbee edited his book, he deliberately made it look like the double-barrelled pump had always been there, and that it was the only one. If this really was his intention, it definitely succeded. Anyone with a background as a laboratory technician will find it absolutely understandable that it was the double-barrelled air-pump that Hauksbee wanted to be identified with.

However, I believe that the reason why the earlier model has been obscured is far more complicated than that it was simply inferior to the classic one. The relationship between the two pumps, and the 'soft' incorporation of the new one into his ongoing activities, can be discussed from several different points of view. I will here emphasize technical and scientific matters.

### 3.2.2.2 Technical differences

The superiority of the double-barrelled pump could be a plausible explanation for the scarcity of explicit writing about the smaller model. But the opposite could also be the case. The fact that there are few indications of this evolution might also mean that the differences between the two models were not that great. In the following I will argue for the latter possibility. To see the difference, a comparison of the two models is required. In the previous chapter, I compared Hauksbee's singe-barrelled pump to the earlier air-pumps by Boyle, Hooke, Huygens and Papin, and showed that his model was better. But how great were the differences between the two Hauksbee pumps?

With the new pump, pumping capacity was about five times greater, correlating to the difference in cylinder volume. It was also much easier to operate, since the required labour was not much more than what was necessary to overcome the friction of system. In comparison, the single-barrelled model required a pull of approximately 7 kg on every outward stroke, as well as a force to withhold the handle during the inward stroke, to prevent it from being sucked into the cylinder too quickly. The accuracy of the in-built barometer of the larger pump was also better. But were the overall differences so great that it would have been appreciated as a basically new device? I will argue that it was not. A comparison of the two models is given in Table 2.

First, a distinct receiver volume could be evacuated in a shorter time and with less effort. But since it most probably was Hauksbee himself, or other assistants who had to pull the handle or move the crank, and not onlookers like Isaac Newton, Edmund Halley, Christopher Wren, and Hans Sloane, it is understandable that the Royal Society did not perceive this difference as a major change. The benefits of easier pumping were first and foremost for the operator. Second, the lowest pressure that the operator could expect was the same. This was limited by the vapour pressure of water, which was used as a sealing agent in both cases. A third point is about the problem of air seeping into the system. This might even have been greater with the large pump, since the total fissure length there was about 4 times longer than with the small one, providing more opportunities for leaks. The double-barrelled pump might therefore at times have been more troublesome, requiring more maintenance for preventing leaks than the simpler model. Fourth, the single-barrelled pump could be transformed to a simple compression engine by replacing the pump-barrel with a compressor-syringe, an option that is evident from an experiment about resilience of bodies in vacuum and in common and pressurized air.[297] To change from rarefied to condensed air in the same experiment would not have been possible with the double-barrelled pump, due to its more compact construction.

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[297] F.Hauksbee, 'Experiments on the Resilition of Bodies in Common Air, in Vacuo and in Air Condens'd', *PT,* vol. 24 (1705), 1846-8.

Finally, when a pressure-increase was required in an experiment, both pumps could facilitate this. Technically speaking, the cock on the double-barrelled pump was a better and more versatile solution than the limited sideway turning of the single pump-barrel. On the other hand, Hauksbee seems to have had gained sufficient control over the pressure-level in the gunpowder and the chafing experiment, both of which were undertaken with the smaller pump.

| Properties | The single-barrelled pump | The double-barrelled pump |
|---|---|---|
| Available | October 1702 | May 1705 |
| Barrels (cylinders) | 1 | 2 |
| Pumping capacity | 250 $cm^3$ | 1240 $cm^3$ |
| Estimated pumping speed | 62.5 $cm^3$/sec | 620 $cm^3$/sec |
| Lowest attainable pressure | ca. 20 mBar | ca. 20 mBar |
| Receiver volume | ca. 12 litre | ca. 12 litre |
| Estimated length of fissures on pump-structure | 30 cm | 120 cm |
| Integrated barometer | yes | yes |
| Self-adjusting barometer scale | no | yes |
| Air-inlet facility | yes | yes |
| Compressed air mode | yes | no |
| Pump stand | optional | yes |
| Estimated cost | £ 6 | £ 12 |

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**Table 2.** Specifications of Hauksbee's single and double-barrelled air-pumps. See Chapter 5 for discussions about the cost.

It is therefore obvious that issues like shorter pumping time, increased accuracy and an improved air-inlet function were not enough to make the whole thing into a fundamentally novel contrivance. So one reason for not particularly mentioning the double-barrelled air-pumps in the 'Journal Book' must have been that the forum saw it not as a new instrument in principle, but more as an improvement of an existing one, where the changes mostly benefited the operator.

### 3.2.2.3 Scientific practice

Another question that arises from a survey of Hauksbee's activities in this period is whether or not the new pump enabled him (or others) to perform a wider range of experiments. The operation of the new pump was faster and less fatiguing, but how did this influence experimental practice? I have undertaken a survey of all of Hauksbee's approximately 120 known experiments, but it turned out to be impossible to point to any (of those requiring a vacuum) that could have been performed with the double-barrelled model only.

Though the two pumps were different, the technical features of the first one seem to have been sufficient for all of Hauksbee's experiments. One example is the chafing experiment, which was first described in the *Philosophical Transactions* in December 1705, accompanied by an illustration of a pump-stand for the single-barrelled pump. This experiment was an important step towards his studies of

electricity, and it is interesting to see that it was initially performed by means of the smaller pump. In the book, published four years later, the description was restructured, but the content was in principle the same. The most striking difference is that the illustration of the single-barrelled pump-stand was replaced with the double-barrelled pump. See Figure 16a and 16b. However, there are no hints in the book that Hauksbee had repeated the experiment with the new pump. If he had redone it, it could anyway not have yielded enough new material to be worth writing about. I think the reason for replacing the image of the pump was simply that he preferred to exhibit his latest contrivance, not that the experiment itself had become changed by the new pump. It is also clear from the sketch of 1707 (Figure 15) that Hauksbee used the single-barrelled pump himself, even after the double-barrelled one was contrived.

In the electrical experiments, where he produced luminous phenomena in rotating glass-globes and cylinders, the role of the air-pump was simply to empty them of air, an operation that could have been done with the single-barrelled pump as well as with the double-barrelled one. In those cases where he tried various pressures in the glass-vessels to see if they had any effects on the luminescence, he could give it as 'a quarter', or as 'a half' of the atmosphere.[298] These could have been approximate values, based on the feeling from letting air into the vessels by the stopcock designated for closing off the vessels. If they were meant as accurate indications, they could be achieved from the single, as well as the double-barrelled pump, since both were equipped with barometers.

In a series of experiments on mercurial phosphorus, published in October 1705, Hauksbee described how light was produced from descending mercury in a barometer tube. It is clear that a double-barrelled pump was used for the purpose, since the mercury was forced downwards by letting air into the receiver 'by the cock'.[299] However, this was most likely the same phenomenon that he demonstrated at his first meeting in the Royal Society on 15 December 1703 where he 'showed a new invented air-pump, and in it, light from descending mercury'. There have been speculations about the background and nature of this experiment. It must have been a demonstration of the light-effect that sometimes can be seen in barometers, here shown in the in-built barometer of the single-barrelled pump, when air was let into the receiver by turning the barrel sideways, causing the mercury to descend. Hauksbee was therefore able to produce barometric light in the barometer of both the single and the double-barrelled pump.

It is also possible to ask about the role of the increased barometer-accuracy, at least concerning the experiments that were performed in Hauksbee's first years at the Royal Society. He seldom gave accurate barometer readings in this period, and it is hard to see how the improved accuracy could have influenced the conclusions of the actual experiments. The pressure-indicating system was technically better on

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[298] *PME*, 48.

[299] F. Hauksbee, 'Several Experiments on the Mercurial Phosphorus', *PT* vol. 24 (1705), 2131.

the double-barrelled pump than on its predecessor, but the question is whether it made any great difference in the early experiments or not. I have found no indication that it did.

There are also other facts that support my claim about the relative equality of the two models as experimental devices. Sales-advertisements, for example, show that the manufacturing as well as the use of Hauksbee's single-barrelled pump was not brought to an end by the introduction of the double-barrelled one. In Hauksbee's first advertisement after the announcement of the double-barrelled pump, in September 1705, the opening sentence was:

> Air pumps both single and double Barrell'd, with apparatus for making the many experiments demonstrating the several properties of air, as its Pressure, Spring and Elasticity, the effect of its absence on the lives of Animals, on Sound and Flame, &c. Having Mercurial Gages adapted to them, shewing at all times the Degrees of Rarefaction to the greatest nicety.[300]

This text was used in at least eight subsequent advertisements throughout 1705, 1706 and 1707. The content indicates that both models were available, and he did not give preference to the newest and most advanced one before the earlier, simpler type. The single-barrelled version was even mentioned first. And more important, both could be used to make the same kind of experiments, and both were supplied with mercury gauges, facilitating 'real-time' measurements. In the introductory advertisement of May 1705, he had devoted much space to spelling out the technical functions and features of the double-barrelled pump. The difference there between the two concepts was given as reduced labour to operate the new one. But when the most common applications of the pumps were described in the following advertisements, both were equally efficient. Therefore, also after Hauksbee's masterpiece appeared on the market, the single-barrelled pump was, and remained, a viable and effective instrument. One example of this is found in an article from 1731 by Stephen Gray, who wrote that 'Mr Wheeler having a 'very good air-pump of the larger sort, made by Mr Hauksbee'; a statement indicating that a smaller pump was an alternative.[301]

In the public lectures, the impact of the double-barrelled pump would certainly benefit the operator, since pumping became quicker and less laborious. But we have no indication that this had any great impact on the kind of experiments that were performed. The experiments in pneumatics were described in the same terms, both before and after the introduction of the classic pump. An important addition came in January 1706, when a 'surprising Experiment concerning the Production of Light in Vacuo' was included in the schedule. However, the new pump on its own could not have made these experiments possible, since this demonstration was identical with the chafing experiment, which worked with both pumps. There is,

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[300] *The Post Man*, 27 Sept (1705).
[301] S. Gray, 'Two Letters from Mr. Stephen Gray', *PT* vol. 37 (1731-2), 397.

however, a possibility that the reduced and easier pumping could have allowed more experiments to be undertaken in the course of a lecture, but we have no evidence of this in Hauksbee's case.[302] The nature and content of these lectures did not change by the introduction of the new pump.

From this it follows that the double-barrelled pump did not induce considerable changes on practical pneumatics in the period. Neither the type of private experiments nor public demonstrations became revolutionized by Hauksbee's masterpiece. The larger pump did not replace the smaller, and both were commercially available together with the same sort of accessories.

### 3.2.2.4 The stabilized form

The leap from Boyle and Papin's pumps to Hauksbee's single-barrelled pump was a much greater advancement than the next step, to Hauksbee's double-barrelled pump. It is clear from the survey above that the double-barrelled pump, in spite of its improved pumping capabilities and nice ornaments, did not revolutionise the pneumatics of the early eighteenth century. If we can talk of a revolution in this case, it had taken place some years earlier, in Hauksbee's introduction of the single-cylinder pump with self-closing valves and cement-free receivers. The 'lack of fuss' around the new pump can therefore be explained by the fact that the Royal Society and others did not see it as a novel instrument 'in principle'. From the philosopher's point of view, the extra features were only technical improvements of an instrument that had already manifested its position.

As I have argued in the previous chapter, the English air-pump did not become black-boxed before Hauksbee entered the scene around 1700. I showed that even though the machine had become black-boxed in the conceptual way by Boyle, the instrumental or technical aspects of the process were not achieved before Hauksbee presented his single-barrelled model. The role of the double-barrelled pump was, as I have made clear above, not crucial here. Its importance is better described by the concept of 'stabilised forms of philosophical instruments', suggested by Anne van Helden on the basis of works by W. Bijker.[303] Helden distinguishes between the stabilized *form* and the stabilized *meaning* as the constituting elements of a stabilized artefact.[304] To me, the stabilized meaning of an instrument overlaps to some extent with the concept of black-boxing, while the stabilized form is exemplified by the difference between the single and the double-barrelled air-pump. I will thus argue that the English air-pump reached its stabilized form in 1705, in the appearance of the artefact depicted in Hauksbee's book of 1709 (Figure 5 and 24).

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[302] In 1714, Desaguliers announced a series of lectures in natural philosophy containing 300 'operations'. It is possibility that quicker pumping with Hauksbee's double-barrelled pump (which Desaguliers used) could have facilitated this high number, but on the other hand, the lectures contained many demonstrations that were independent of air-pumps. See Morton and Wess (1993), 55, and *The Daily Courant,* 18 Jan (1714).

[303] W. Bijker, *Of Bicycles, Bakelites and Bulbs* (Cambridge, Mass, 1995).

[304] A. C. van Helden, 'Stabilised forms of Philosophical Instruments', *Proceedings from XVIII International Scientific Instrument Symposium, Moscow 1999* (Moscow, 2002), 67-79.

The arrangement with two parallel and interconnected cylinders, operated by a crank in a rack and pinion system in the front of a pump-structure, became the standard form of the instrument, and one that lasted to the twentieth century.[305] Of course, a series of variations upon this form occurred over time. Hauksbee's concept was taken up in Holland and Germany with some technical differences, but in an overall recognizable form nonetheless.[306] In England, the form survived in both smaller tabletop pumps and larger, freestanding instruments like the one depicted in Wright's painting.[307]

Hauksbee's pump-concept provided possibilities for a long range of private and public experiments in natural philosophy. It would take half a century before his pump-technology became superseded, and even longer before the form itself became replaced.[308]

## Conclusion

I have in this chapter discussed Hauksbee's double-barrelled air-pump, and shown how it was introduced and incorporated in his activities during 1705 and 1706. Technical issues like pumping speed, leak tightening, and lowest attainable pressure have been explained and compared with similar characteristics of the smaller pump. Further, I have shown that even if the system of the two interconnected barrels was close to Papin's, and the rack and pinion system to Boyle's, all the important details like self-acting valves, sealing methods, and pressure measurements were transferred from the single-barrelled model. I found no direct evidence that Hauksbee had worked with Boyle, Hooke or Papin. Such a connection cannot be ruled out, and though it would have been important, it was not decisive for his career in the same way as his commercial cupping engagement was. I have also shown that both Hauksbee and others compared his pumps to those of Boyle, and not to Papin's double-barrelled contrivance. This indicates that Papin's pump was not as crucial for the general development of the air-pump as is commonly believed.

Hauksbee's double-barrelled pump was a masterpiece and represented the state of the art of the period. It was more advanced than its predecessor, but the advantages consisted mostly in a shorter pumping time and less labour for the operator, which did not increase the range of possible experiments. The Royal Society, for instance, did not appreciate it as a novel instrument, but possibly as a refinement of the earlier version that already had manifested its position. In the

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[305] Leppin & Masche, *Physikalischer Apparate* (Elberfelt, Pfingsten, 1896), 23.
Other air-pumps that reached stabilized forms were Papin's single barrelled pump with a stirrup, and Senguerd model with its characteristic large, oblique cylinder.

[306] For example by Jacob Leupold (ca. 1710) and 'sGravesande (1722). See: Helden (1991).

[307] A discussion on this pump is given in Chapter 5.

[308] Smeaton (1753), 415-27.

previous chapter I claimed that the English air-pump was not black-boxed by either Boyle or Papin's devices, but with Hauksbee's single-barrelled pump. In this chapter, I showed that the pump finally reached its stabilised form by the shape, appearance and functions of the double-barrelled pump. The air-pump was now ready for applications that would become typical for the eighteenth century: investigations and demonstrations of natural phenomena in both public and private settings, where the attention had moved away from the instrument and towards the effects that they could produce, for example, in scenes like in Wright's painting. These issues are discussed in the second part of my thesis.

Part 2

# Using the air-pump

# Chapter 4
# The new vacuum

## Introduction

In an account about attrition of various materials in vacuum, published in 1709, Hauksbee, wrote that:

> A Description of the *Air Pump* being before given, I shall forbear taking any further notice of it, saving what immediately relates to the following *Experiments*.[309]

In this chapter, I discuss a series of applications where the air-pump was 'not taken much notice of', but where the emphasis was put on new experiments and pump-accessories. I also examine the extended uses of the term 'vacuum'. My aim is to show, now with the air-pump being conceptually black-boxed and having a stabilised form, how the development of pneumatics continued. I argue that the relationships between the pump and the pump-accessories, as well as between the pump and the vacuum, changed in this period, and very much due to Hauksbee's activities. I make it clear that a practical separation of the instruments from the pump, and a conceptual separation of the vacuum from the receiver, took place. Starting with Guericke and Boyle, I will show that during the seventeenth and the early eighteenth century, attention moved away from the pump and towards its external instrumentation. Further, I show that in parallel to this, the expression 'a vacuum' became widened from describing an empty space (like the 'Vacuo Boyliano') into a practice where it also could denote one physical parameter among various others. I see these two events as important issues in the 'second chapter' in the history of the English air-pump, if we name the events described in *Leviathan*

[309] *PME*, 21.

*and the air-pump* as the first. Hauksbee had earlier managed to turn the pump into a reliable and commercial product; now this process was continued by the availability and use of external instruments, and of new experiments.

A distinction between the pump and its additional equipment is necessary to understand how this development took place. Instrument-historians have until now not distinguished clearly between these elements, neither between the pumping and the experimental practice. I will make such a division, recognising pumping as the pumping-action itself, for example pulling the handle or turning the crank, as well as the problem of leak-tightening. This corresponds with the necessary operations and attentions for creating the vacuum in which the experiments could take place. The other issue, experimental practice, relates to use of the external apparatus and how easy they were to set up, as well as to manipulate and to replace the various instruments in the receivers. These issues were more or less intertwined in the earlier pumps, but became differentiated over time.

The air-pump evolved from an original state where the pump-cylinder and the receiver were integrated in one unit: first into a system where the pumps possessed separate barrels and receivers, and then into one where to pumps used a series of specialized receivers – an application typical for Hauksbee and his followers. I give examples of air-pump practice at this stage, discussing animal-tests, glass breaking, and the firing of gunpowder in vacuum, showing that such experiments, often performed in purpose-made receivers, must have contributed to demythologize the vacuum concept, making it into a technical term. This was achieved by visualization and explaining phenomena such as pressure, spring and weight of air.

Further, I show that the air-pump developed to yet another stage, where pump-accessories came to be regarded as more significant than the pump itself. I elucidate this by discussing a few of Hauksbee's instruments: the rotating globes and cylinders and a hollow prism, all of which could be evacuated by the pump. I argue that the air-pump in these cases had become downgraded to a supplier of vacuum only, with no other distinct purpose in the experiments. These instruments became used dislocated from the pump, and the vacuum was only one of the elements in the tests.

In addition, many air-pump experiments were made on other fields than pneumatics, indicating that pneumatics had become a service agency in other disciplines.

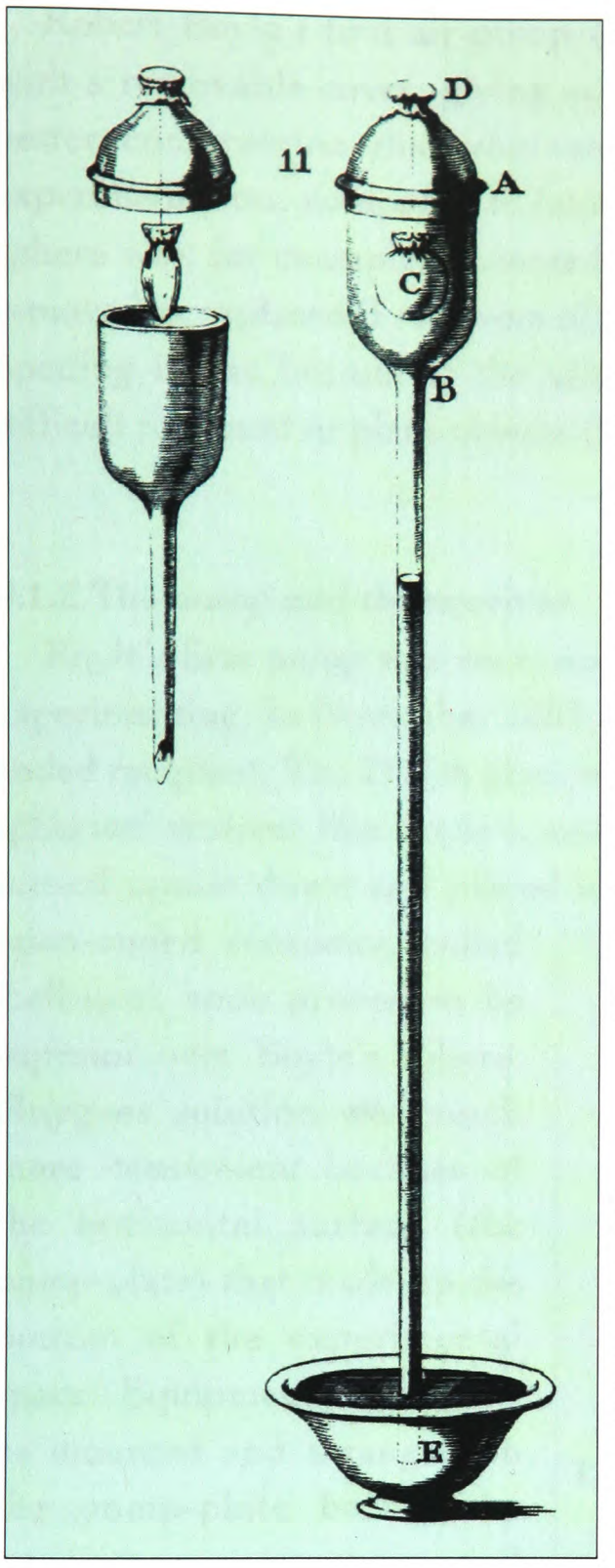
## 4.1 Air-pump developments

An early attempt to describe the various stages in the development of the English air-pump was made by G. Wilson in 1849. He saw Boyle's first pump of 1659 as the initial step, characterised by a single barrel and a globular receiver that were directly connected through a stopcock. The next step came with Boyle's second pump, which had a bell-shaped receiver that was separated from the pump and placed on a board (1667). While these two pumps had one cylinder and were driven by a rack and pinion, the pump representing the third stage had two interconnected pistons driven by a cord over a pulley, and possessed self-closing valves (1676). Wilson attributed this pump to Papin and recognised that it was almost absent in the eighteenth-century literature. The next and final stage was a combination of the rack and pinion and the two barrels, a construction that Wilson dated to 1704 and argued belonged to Hauksbee, but was possibly 'a relic of Hooke'.[310] Wilson's scheme was reprinted in R.E.W Maddison's book on Robert Boyle from 1969,[311] and referred to in *Leviathan and the air-pump*. According to the authors of this well-known book, Wilson's review was then (1985) still the best overall account of the history of the English air-pump that existed.[312]

However, I think it is time to modify and extend the list with more emphasis on how the air-pump developed as an experimental device and not such exclusive attention on the number of barrels or how it was operated. Relevant issues here are, for example, how access to the experimental space improved, as well as how this space became separated from the pump-structure. I see such categorization as helpful for understanding the advancement of the pump as an instrument for both demonstrations and research, as well as how the term 'vacuum' became extended into new meanings in the period.

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[310] Wilson (1849), 331-2.
[311] R. Maddison, *The life of the Honourable Robert Boyle* (London. 1969), 227.
[312] Shapin and Schaffer, (1985), 26.




### 4.1.1 The first air-pumps

I will categorise the development in four groups, placing Guericke's pumps, the glass-pumps by Accademia del Cimento in Florence, and Boyle's first construction in the opening category. In all of these instances, the pump and the receiver were in practice integrated into one unit, with no (or at the least restricted) access to the receiver. Guericke's first receivers were made of wood or copper, and had no arrangements for placing objects or instruments in the evacuated space.[313] See Figure 28a. The concept by Accedemia del Cimento was different, with the pump (the barometric tube) and the experimental space (the bulb on top of it) integrated in a single piece of glass.[314]

**Figure 33.** The pumping method by Accademia del Cimento. (Florence, 1660s). A Torricellian vacuum became created in the enlargement at the top of the tube by first filling it with mercury, which then was dropped down in the tube and into the basin below. In Lowthorp's experiment, (Section 4.3.2) the top-bulb was replaced with a prism. From W.E.K. Middleton, *The History of the Barometer* (Baltimore, 1964), 63.

The bulb had a lid for inserting objects, but experiments were restricted by the relatively small space inside the bulb, see Figure 33.[315]

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[313] Guericke had, for example, one receiver made of two wooden barrels, one inside the other, with the space between them filled with water to prevent leaks. The inner volume was pumped by a through-going tube. After pumping, the vessel could be closed off by a stopcock, but there was no access to the inner space without dismantling the barrels. Guericke described spherical glass-receivers for experiments with birds, mice, timepieces, bells, candles, etc. in vacuum, first after Boyle had published his work. He performed some significant measurements of the weight and pressure the air, but his overall contribution to the air-pump as a scientific instrument was small. See Helden (1991).

[314] Middleton (1964), 61-4. A good description of Accademia del Cimento is given by Middleton in: *The experimenters* (Baltimore, 1971).

[315] See the Introduction for more details on these early pumps.

Robert Boyle's first air-pump (Figure 6) had a large, spherical glass-receiver with a removable cover, giving access to the experimental space. It was a much better construction than the two previous ones from the aspect of making experiments, but compared to later models, it had some clear disadvantages. The sphere was, for example, cemented to the top of the barrel and could not easily be removed or replaced if receivers of other shapes were preferred. The funnel-shaped opening in the bottom of the sphere was an inconvenience as well, making it difficult to mount or place objects there in a firm way.

### 4.1.2 The pump and the receiver

Boyle's first pump was soon surpassed by another model regarding convenient experimenting. In November 1661, Christiaan Huygens built a pump with an open-ended recipient. The Dutch glass-workers had had problems with manufacturing a spherical receiver like Boyle's, and Huygens had simply used an apothecary's jar turned upside down and placed it upon a metal plate above the barrel.[316] These open-ended receivers, called 'bell-jars', soon proved to be superior over Boyle's sphere. Huygens solution was much more convenient because of the horizontal surface (the pump-plate) that made up the bottom of the experimental space. Equipment could now be mounted and arranged on the pump-plate before the receiver was in place, and receivers of different sizes and shapes were allowed. On his later versions, the pump-plate was moved to one side of the pump. See Figure 34. Robert Boyle adapted Huygens system with open-ended receivers on the later version of his second pump, these receivers being mounted on a base plate adjacent to the

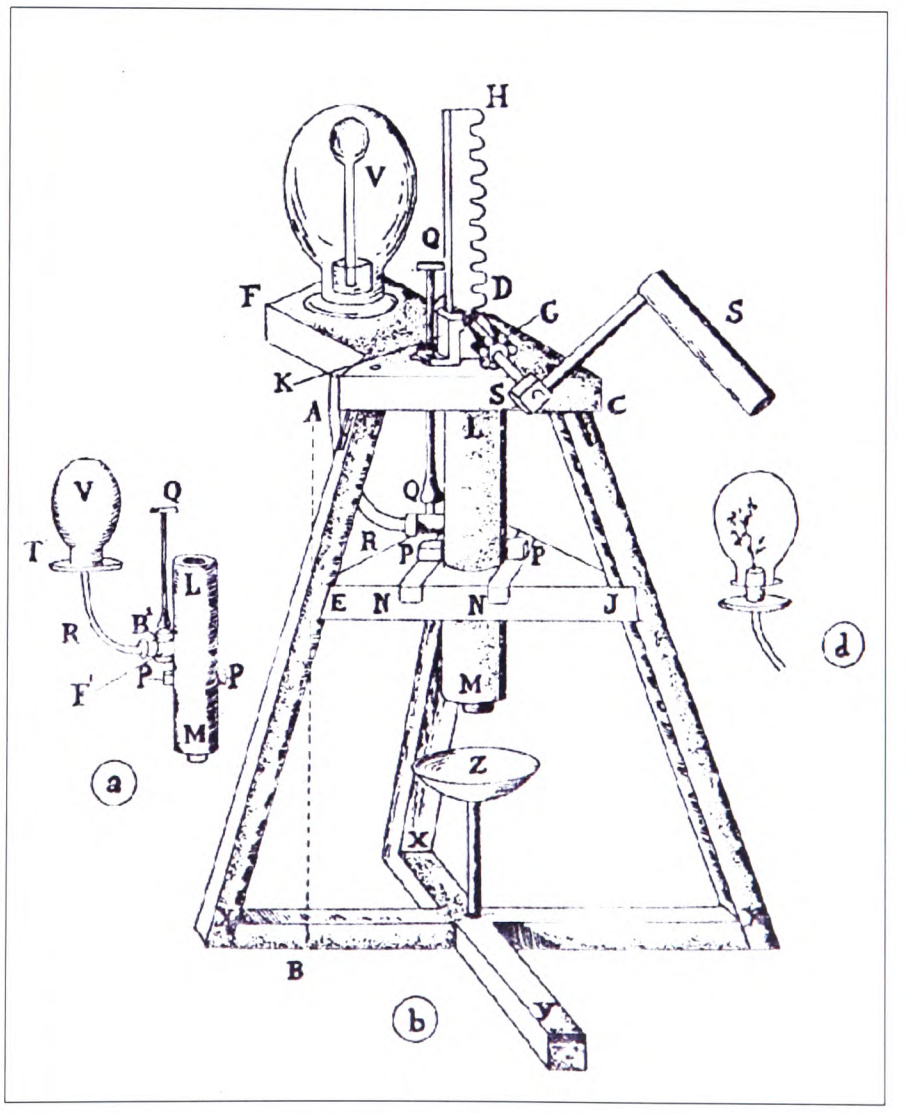



**Figure 34.** Air-pump by Christiaan Huygens. May 1668. L, Pump-cylinder; V, receiver; F, pump-plate; d, receiver with plant. From Stroup (1981), 150.

[316] Stroup (1981), 131-2. Stroup indicates that this could have been the reason for Huygens adaptation of this shape of the receivers, while Shapin an Schaffer present it as 'crafted to improve the integrity of the pump' See Shapin and Schaffer, 237.

pump (Figure 18). This system was applied by Papin on his double-barrelled air-pump of 1668, and also used by the Dutch instrument-makers on their first commercial air-pumps from about 1670. The bell jar, placed on a separate plate, became standard for all air-pumps where a general space for various experiments was needed, and was also used by Hauksbee on his single and double-barrelled pumps.

Following the scheme above concerning experimenting, I see it as natural to describe the introduction of the bell jar as a second stage in the development of the pump. Now the cylinders and the valves (or stopcocks) were components in the section that contained the pumping functions, while the receiver and the pump plate were separated from it, making up the location for the experiments. Its greatest gain was the convenience obtained by the removable receivers.

### 4.1.3 Specialised receivers

If we proceed and undertake a study of further developments of the air-pump, we can observe technical improvements of the machine as such, as well as an expanding area of applications. In the following period in Holland and France (before 1700), the air-pump was turned into a reliable and commercially-available instrument. At the same time, the number of applications of the pump was growing, represented by a range of new, specially-made receivers and accessories, intended for various experiments. Before the turn of the century, a few such pieces of apparatus were available with the pumps from the Musschenbroek workshop.[317] The emphasis had changed from pumping and leak prevention to the use of specially designated equipment together with the machine.[318] Pumping and leak-tightening were still essential parts of an experiment – but now that went without saying.

In England, Hauksbee had from the start applied receivers that were equipped with devices for particular purposes, for example the receiver supplied with a 'feed-through' for linear and rotary movements in the vacuum. See Figure 6. In his first advertisement concerning separate air-pumps, in October 1702, Hauksbee announced 'Air pumps, with Apparatus for making all manner of Experiments proper to be made in Vacuo Boyliano'.[319] In his publication, Hauksbee described receivers of different shapes and sizes capable of performing various tasks by means of specially-made accessories attached to them. One example is the receivers with special gadgets made for demonstrating light from mercury droplets in the vacuum; another the dispenser for dropping gunpowder onto a red-hot iron (Figure 32); yet another a tall receiver holding a mechanism for dropping marbles

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[317] de Clercq (1997), 112.

[318] Several different receivers are also found with Boyle, but as long as technical problems and the struggle for social acceptance of the pump were dominant, his apparatus fits best into the second group.

[319] *The Post Man*, 27 Oct. (1702),

onto a glass plate. The largest air-pump appurtenance by Hauksbee was the arrangement that consisted of a wheel and pulley, and a receiver with through-going axle for rubbing substances in the vacuum (Figure 16). A good example of additional equipment accompanying the air-pump is given by Hauksbee's associate, William Vream, who supplied a text on air-pump experiments with a cut of 30 specially-made receivers, intended for various experiments with a Hauksbee-pump.[320] See Figure 35. The receivers were presented as separate devices with their own function; the reason to place them on the pump-plate was simply to evacuate them.

This practice, first carried out by the Dutch workshops and then in England by Hauksbee and his followers, can be described as a third stage in the development of the air-pump. The pump itself had become an unproblematic and reliable instrument; now emphasis was instead put on the variety of experiments that could be performed by means of specially-designated accessories. The significance that was given to these external instruments is an indication of a shift in attitude towards the pump as well as to the use of the term 'vacuum'. The emphasis had moved away from the machine that created the vacuum and towards the experiments that were performed by means of it, and to the explanations of the demonstrated phenomena. According to the texts by Hauksbee and, for example, Vream, 'vacuum' started to become described and conceived more and more as a technical condition that was produced by the pump, but not necessarily applied there. Examples of air-pump experiments at this stage are given in Section 4.2.

[320] Vream (1717). Vream's years of birth and death are unknown.

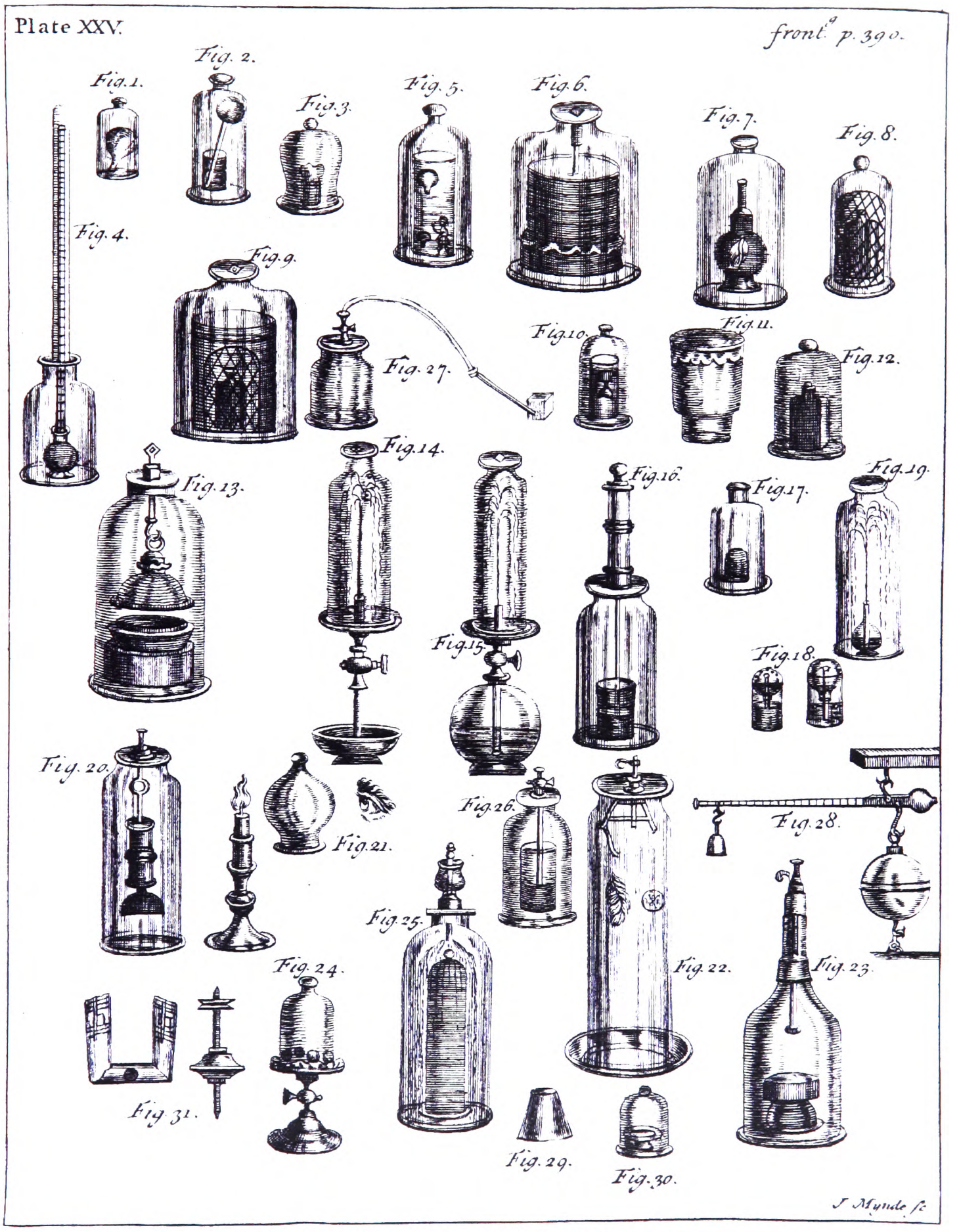



**Figure 35.** Specialised receivers by William Vream.

### 4.1.4 Separate instruments

However, I think it is possible to talk of yet another stage along this line, characterized by some of Hauksbee's most advanced instruments. Here the process of separating vacuum-related experiments from the air-pump was taken to an end. A close reading of Hauksbee's accounts demonstrates that some of the apparatus he used with the air-pump can be regarded as something more than just 'air-pump accessories'. Their physical construction and their use make it clear that they had specific functions when they were exhausted by the air-pump, but on the other hand, they had also functions *without* being pumped. When used, they were disconnected and dislocated from the air-pump, a practice very far from, for example, Boyle's. One example of such a device is a glass globe that could be connected to the pump by a copper tube and evacuated, and then closed off by a stopcock. When filled with some amount of mercury and removed from the pump, Hauksbee was able to produce light by shaking it. He used it in his study of light from mercury droplets, and made experiments both with vacuum and with air inside it.[321] Another example of apparatus that worked detached from the pump is the rotating glass-globes and cylinders, which he applied in his experiments on light and electricity.[322] See Figure 36. Yet another example is a hollow prism for studies of the refraction of air.[323]

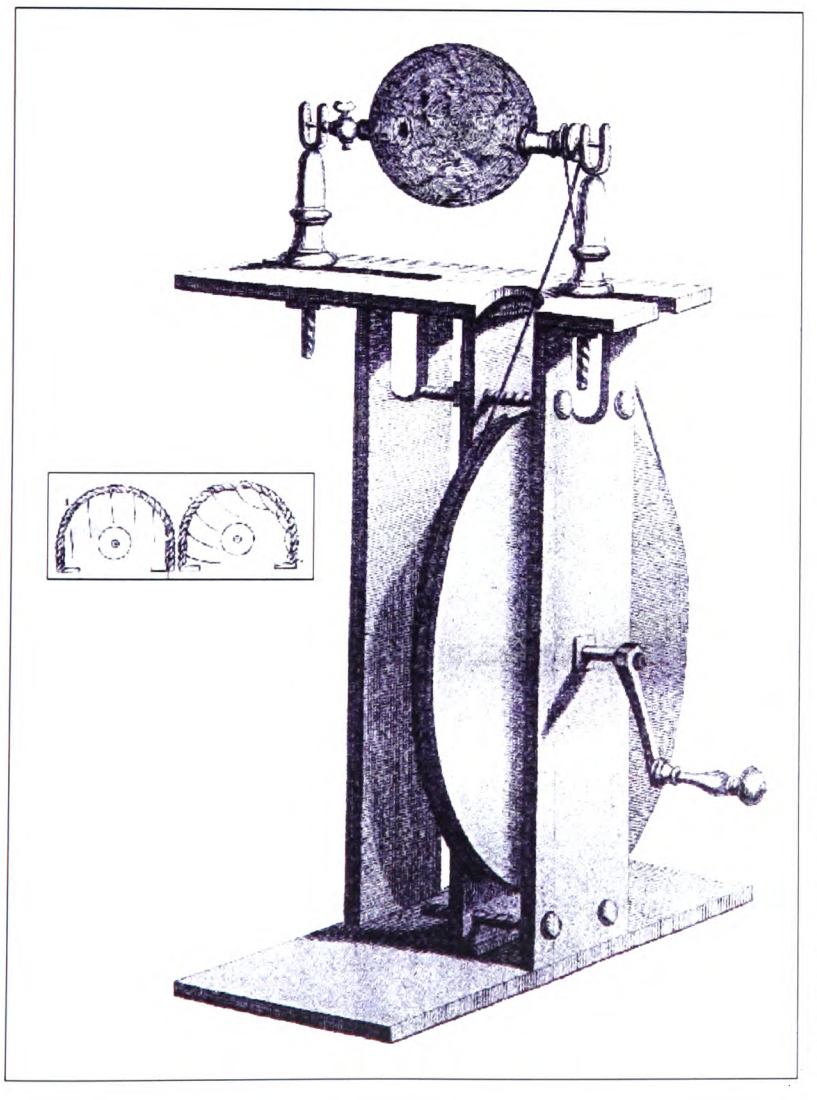


**Figure 36.** Hauksbee's rotating globe for studies of light and electricity. The insert (part of the original picture) shows metal hoops with wool-threads for detecting electrical attraction and repulsion. The circle in the centre is representing the globe (London, 1706).

[321] *PME*, 16.
[322] *PME*, 45, 65.
[323] *PME*, 225-30.

I will discuss the two last instruments and their functions in some depth in Section 4,3, and show that such apparatus represented a fourth stage in the development of air-pump instrumentation, and also contributed to transform 'vacuum' into a technical term. A diagram showing the four stages of the air-pump as an experimental device is given in Figure 37.

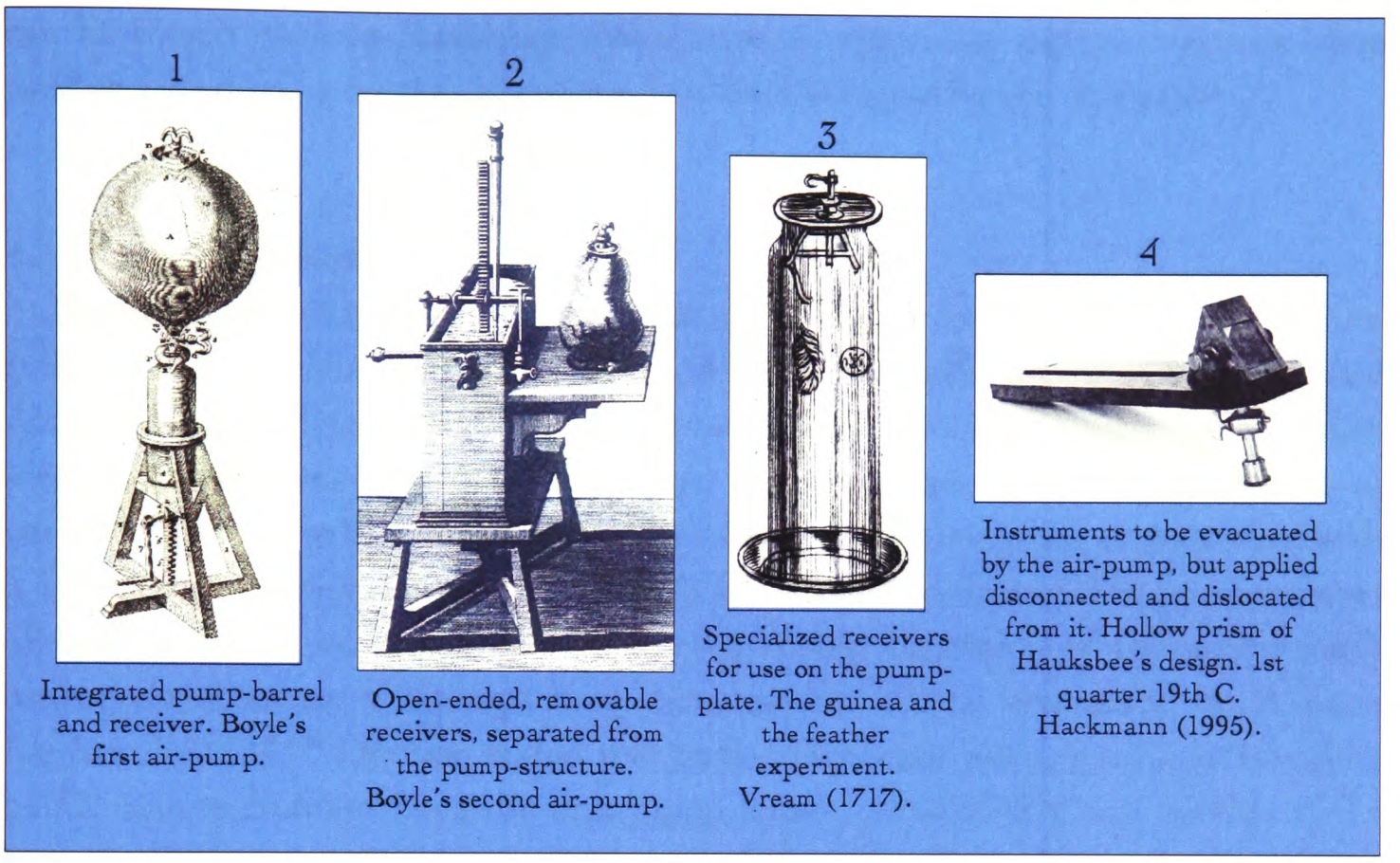



**Figure 37.** The four stages of the air-pump as an experimental device.

## 4.2 Experiments in specialized receivers

I will here discuss three selected experiments that were typical at the third stage. These experiments, concerning animals in vacuum, air, and gunpowder, were all standard operations in the public lectures given in London during this period. One mark of these lectures was the cooperation between an instrument-maker and a natural philosopher. This included collaborations between Hauksbee the elder and James Hodgson (1672-1755), Francis Hauksbee the younger and William Whiston (1667-1752), and William Vream who worked with John Desaguliers. Another feature was the use of printed material, for example course syllabi and newspaper-advertisements. A third and typical characteristic was the extensive use of experiments and demonstrations. The experiments in pneumatics were mostly performed in specialised receivers that became evacuated by the pump.

Larry Stewart has discussed the general importance of these lectures in his book *The Rise of Public Science*, and I will in the next chapter go deeper into the role of both the instruments and the instrument-makers in these undertakings. Here I will show how air-pump experiments must have assisted in familiarizing the public with the idea of a vacuum, while also transforming the vacuum into a simple experimental condition.[324] With emphasis on the instruments, which in many cases can be traced back to Hauksbee, I will make it clear that the vacuum was often used as a method to display phenomena in mechanics and other disciplines.

### 4.2.1 Life in a vacuum

Experiments with living creatures in the vacuum are found in most lecture syllabuses from the period. In the previous century, Boyle, Guericke and Accademia del Cimento had all performed experiments with birds, fishes, frogs, insects and mammals in vacuum. There seems to have been a high degree of curiosity among the first experimenters who possessed air-pumps or glassware with a Torricellian space that were big enough for living test-objects. The consequences of lack of air on animals was well-known in the beginning of the eightheenth century, and an early attempt to systematise the effects was made by William Derham in 1704.[325] Derham stated that birds, dogs, cats, mice, etc. die in less than half a minute counted from the first pump stroke, a mole after one minute, and a bat after seven or eight minutes. Insects such as wasps, bees or grasshoppers seem to die first after two minutes, but could come to life again in fresh air after being kept in a vacuum for twenty-four hours. Snails did not seem to be much affected at all, and could at least live one night and one day without air.[326] Experiments with living objects were also performed in condensed (compressed) air, where a higher air pressure than normal was used. A study of public lecture syllabi reveals that displaying effects of lack of air on animals was standard, and was performed in the first lectures of Hauksbee and Hodgson in 1705. Looking more closely, it becomes clear that the lecturers applied their living objects for at least three different purposes. First, the tests were used for demonstrating and explaining the importance of air in the life of animals. The same experiments were also used for explaining basic properties of the atmosphere like its weight and pressure. A third purpose was to demonstrate the characteristics of air as a substance (gas). These topics are not always described directly in the records of the lectures, but emerge by studying the content of the relevant course descriptions, and by the way the matter was organized. I will first give an overview of the content and the relevant apparatus, and then discuss how the experiments were explained. This will show that the air-pump had become secondary.

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[324] Stewart (1992).
[325] Derham (1714), 8.
[326] Harris, *Lexicon Technicum* (London, 1737), under 'Vacuum'.

Not much specific information is found in Hodgson/Hauksbee course syllabi. The first one (December 1704)[327] said that the 'usefulness of air for conservation of life' was going to be demonstrated, and in a later one they planned to show that air was 'essentially necessary' for life.[328] However, indications on how such experiments were undertaken can be found in some of Hauksbee's articles in the *Philosophical Transactions*. One article is an account on fishes in a water tank inside the receiver,[329] another one about a cat breathing "infected air".[330] From the 'Journal Book' of the Royal Society, we also learn that Hauksbee performed experiments on birds, both in a vacuum and compressed air.[331] All these experiments must have been natural to repeat in the public lectures.

Hauksbee Junior and William Whiston had one experiment called 'respiration' filed under the heading of 'experiments which mostly were performed in glass-tubes, before the air-pump was invented.[332] Their aim was to show the 'effects of the weight and spring of the air' as well as 'respiration', through means of various instruments. No more details were given; these experiments did not necessarily involve animals at all, as it could have been some sort of 'lung glass' that was used (see below). However, they had three explicitly animal-experiments on the schedule. Close to the end of the course they demonstrated the influence of rarefied, condensed and burnt air on animals.

Since the syllabuses so far contained few practical details about these experiments, we have to study two books from 1717 to gain more insight into the issue. Desaguliers described in *Physico-Mechanical Lectures* how air became poisonous when passing through glowing charcoal, spirit of wine and red-hot brass, but not through red-hot iron or copper.[333] Desaguliers described also several experiments concerning animals in compressed air, stating that few animals will die under such circumstances.[334] This text was supposed to be read together with Vream's book *A description of the air-pump,* where the practical details of this experiment are found. In Vream's book we find several 'life' experiments. He demonstrated that cats and other animals die in a vacuum, 'if the air was not let in again very soon'.[335] The aim of that particular experiment was to show the effects of the spring or elasticity of the air. He also explained that if fishes were kept in a water tank in a receiver, which subsequently became evacuated, the fishes would

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[327] *The Daily Courant,* Sat. 9 Dec (1704), The lectures commenced 15 Jan. 1706.
[328] F. Hauksbee, Sen. and J. Hodgson, *Hydrostatical and Pneumatical experiments,* (London, Undated, ca 1708), 4.
[329] F. Hauksbee, 'An Account of some Experiment touching the keeping of fishes in Water', *PT,* vol. 27 (1712), 431-4.
[330] F. Hauksbee, 'Experiments concerning the Effects of Air Pass'd through Red Hot Mettals', *PT,* vol. 27 (1710), 200. The cat survived, 'but was very fierce and did spit and fly at any one that offered to touch her; and it seems hazardous for anyone then to attempt it'.
[331] The 'Journal Book' (1702-1714), 26 April 1704.
[332] Hauksbee and Whiston (1714), 3.
[333] J. Desaguliers, *Physico Mechanical Lectures* (London, 1717), 39.
[334] Ibid, 40.
[335] Vream (1717), exp. 9.

rise to the surface, being unable to dive. According to Vream, this was because the airbladder inside them would expand when the air-pressure above the water was removed. The fishes would become lighter than water, and were therefore incapable of swimming to the bottom. However, in some cases the airbladder broke, causing the fishes to sink. Two other experiments dealt with living creatures. In one Vream accounted for the practical details of how to let animals breathe infected air: the receiver was first evacuated, and then air let in again through a tube ending in a piece of glowing charcoal or in the cavity of a red-hot brass piece.[336] When the receiver had been filled with this kind of 'effluvia' it was lifted up for a moment and an animal let in. Vream reported that they would die immediately in charcoal-infected air, but could live for a while in air from red-hot brass. He had also a short note stating that flies will not die in a vacuum, but are unable to fly.[337]

The most advanced instrument in these tests was the artificial lung, a special receiver containing one or two bladders. (The lung-glass). It is a good example of an air-pump accessory with a distinct function, and where the pump itself was seen as a separate instrument. Not many details of the original instruments could be found, and none has survived. I was, in spite of this, able to achieve a reasonably good understanding of the device by studying the old descriptions and images, as well as examining a few later, similar, objects.[338] See Figure 35, *Fig 7.*

Vream described lung-glasses with one bladder, while Desaguliers described lung-glasses with two, which made for a closer analogy to the set of double lungs found in animals. See Figure 38 for a functional drawing. The bladder, modelling the lung, was tied to a glass-tube that was cemented to the brass-screw, which would in turn fit to the brass-head of the spherical bottle. The bladder was placed inside the bottle, but in order to get it there the bladder had to be compressed first to squeeze it through the opening, before being blown up again. The screw would then be tightened with a key, and a leather gasket used for a seal. When the device was placed under the receiver and evacuated, the air inside the bladder would be sucked out. The atmospheric air in the confined space between the bladder and the glass walls would expand and squeeze the bladder. This experiment was used to show how the lungs of animals in a vacuum became compressed through expansion of air in the Thorax when lungs were emptied of air through the windpipe.

Other devices were needed for the animal-tests, most of them rather simple. When animals and fishes were used to demonstrate the pressure and spring of the air, only an air-pump with a bell-shaped receiver and a vessel with water were

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[336] F. Hauksbee, 'Experiments concerning the Effects of Air Pass'd through Red Hot Mettals, &c', *PT,* vol. 27 (1710), 199.

[337] Vream (1717), exp. 49.

[338] Inventory lists from the following museums and collections have been checked: Museum of the History of Science, Oxford; Museo di Storia della Scienza, Florence; The King George III Collection, the Science Museum, London; Teyler's Museum, Haarlem; and Museum Boerhaave, Leiden.

needed. When animals were going to be exposed to infected air, the air was produced in a piece of charcoal or other such means and then sucked into the receiver through a tube. See Figure 35 *Fig 27.* Facilities to heat and handle the charcoal, the iron-piece and other such materials were of course required as well.

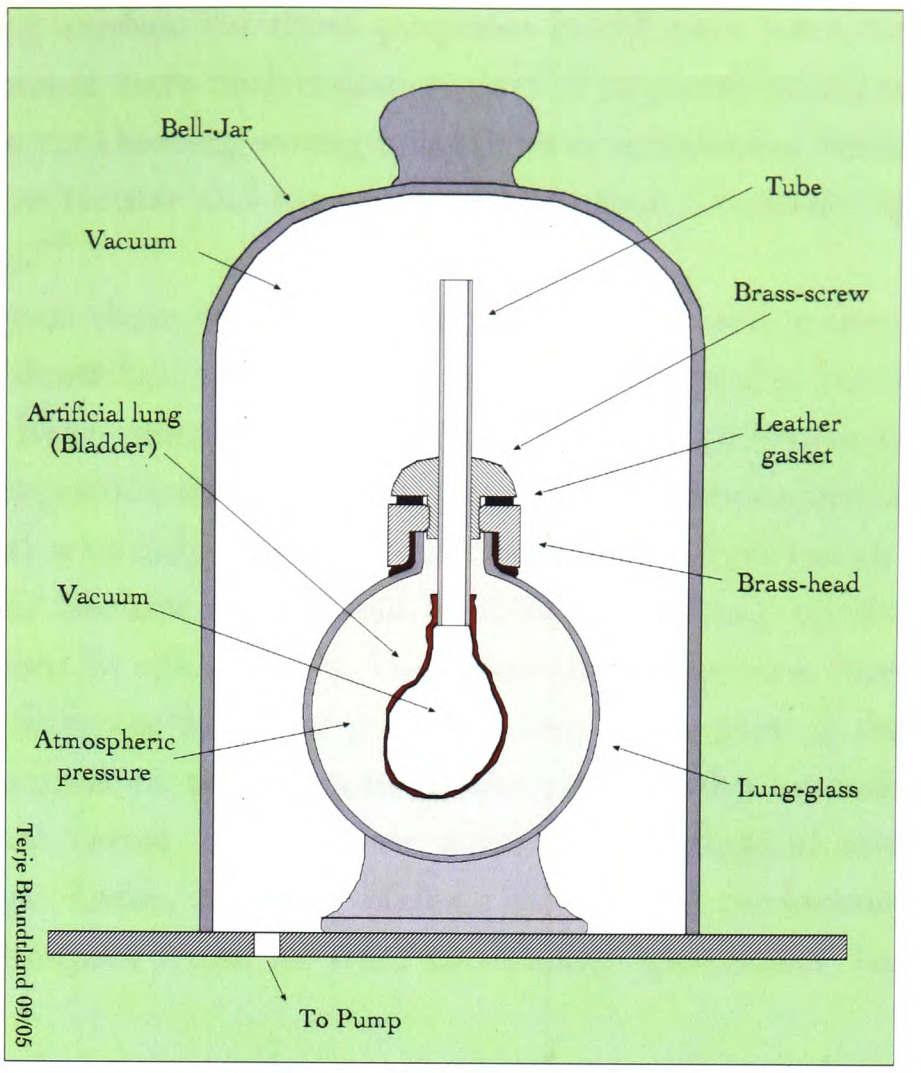



**Figure 38.** The lung-glass.

It is clear that such experiments, when shown in the public lectures, were not made for entertainment or simple demonstrations only, but served pedagogical purposes in pneumatics and other fields. In cases where animals and fishes were used for demonstrating effects of rarefied air, we can say that they were used as *sensors*. By this I mean that they were used to give *indications* of what was happening when the air was sucked out of a receiver. If air was removed by a pump or syringe from a bladder, it would become compressed due to the surrounding atmospheric pressure. If the same experiment was performed with a bladder in a closed container with atmospheric pressure, the spring of the air that was left inside the confined space would expand and make the bladder collapse. Similarly, if the air in the lungs of an animal was removed, the spring of the air in the flesh of the body would make the chest expand and force the lungs to collapse. The fish-experiment was in fact similar to those with bladders submerged in water tanks in receivers, which rose to the surface when the air was taken away, due to expansion of the air in the bladder.[339] From this point of view, experiments involving fishes, cats and mice were in these cases not applied for studies of animal life at all, but for showing the mechanical properties of air as a substance (gas), and of the atmosphere. However, these experiments demonstrated one aspect of the connection between life and pneumatics, as they saw it. The description of the artificial lung, for example by Desaguliers, indicates that one aspect of respiration was understood as *mechanical* (Figure 38). If the possibility of chest movement, and consequently the expansion and contraction of the lungs was prevented, the animal

[339] Vream (1717), exp. 6, 7.

would die. One reason for using animals for these purposes could have been the pedagogical aspect. The experiments were undertaken as part of demonstrations of basic physical phenomena, but a cat showing strong symptoms of uneasiness inside the glass was something more spectacular and easy to remember than a contracting and expanding bladder in a glass.[340]

Another type of experiment was those involving 'infected' air. This was quite a different experiment than those described above. There, animals were used to show pneumatic phenomena, while here pneumatics was used to show phenomena concerning animal life. The experiments were performed under atmospheric pressure and the air-pump itself was only used as a generator for poisonous air. Pneumatics had in theses cases become a practical method for setting up the necessary experimental conditions in other fields. Demonstrations showing how long animals could survive in different kinds of poisonous air were part of the course, but we find no explanations or speculations in the text of why animals behaved like this, or in modern terms, of what we would call biological and chemical processes in the lungs. Later, Stephen Hales (1677-1761) performed experiments based on this techniques when he tried to develop 'gas-masks' for mine-workers. See Chapter 6.

In this period we see a tendency towards an organised use of animals as indicators, and towards systematic investigations around the question of respiration and the role of common air in sustaining life, investigations applying the air-pump. These contrasted starkly with experiments on animals of the 'what-happens-if-we-' type. Criticism of animal experimentation began to be heard among educated lay-people in this period, but no indications of pity or moral objections are found in our source material.[341] The only exception was in Holland, where s'Gravesande wrote that it must be hurtful for animals to be in compressed air, 'if they do not die soon'.[342]

### 4.2.2 Breaking glass

The spring and pressure of air was one of the main issues taught in the public lectures. Air is an invisible substance, but the lecturers used a variety of methods to make its properties undeniable. Animals were used to illustrate such properties, and another method was to break bottles and burst bladders by rarefied, condensed and common air. Like the study above, a thorough examination of the course-syllabi shows that these experiments were used for demonstrations of several different issues. It also becomes clear that the pump is hardly ever mentioned in these texts.

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[340] See Figure 49 (Davenport's cat).

[341] N. Rupke: *Vivisection in Historical Perspective* (London 1990), 28-30.
See also Vream (1717), Exp. 44.

[342] s' Gravesande, *Physices Elementa Mathematica* (2 vols, Leiden, 1720-1), i, 233.

Topics regarding weight and elasticity of air were addressed in Hauksbee and Hodgson's first lecture series, and were soon standard elements in the others programmes. However, we have to look to Vream to find the best technical description of how these demonstrations were performed in practice. One way was to place a closed bottle with flat sides (a square phial) into a receiver and operate the pump. Since the bottle had been sealed off and contained atmospheric air, and the external air was taken away as the receiver was emptied, the pressure exerted by the spring of the air inside would blow the glass bottle into pieces. To increase the effects, the bottle could be submerged into water and kept there, and when the air above the surface was pumped away, the glass would break 'violently',[343] or 'with a shock so great that the whole pump would shake'.[344] The reason for performing experiments with submerged bottles was simply to make the effects more striking for the audience. This experiment was also performed the opposite way, with a vacuum inside the bottles and normal air-pressure on the outside. Most of the philosophers had this experiment in their repertoire, and Vream provided many details. He described how to make a one-way valve by mounting a piece of bladder-material on top of a square glass-phial so that 'the air can come out but not go in again'.[345] Placed in a wire-cage inside the receiver, the bottle would become emptied of air when the pump was operated, but when the air was let in again it would maintain its vacuum and the external pressure would cause it to implode.[346] Hodgson and Hauksbee also performed this experiment (1706), but with the evacuated phial submerged in water.[347] Desaguliers described similar experiments with compressed air.

Several other experiments were performed to encourage an understanding of the spring and the pressure of the air. The easiest method was simply to lay the hand over the opening of a short glass cylinder while the other end was placed over the pump-opening. By operating the pump the hand would be sucked in, showing the pressure of the external air. Vream also broke plates of window-glass by laying them over a brass ferrule and operatating the pump.[348] Another instructive task was to place a truncated brass cone over the pump-opening, about 1.5 and 4-inch diameter at each end respectively. A glass plate on top of the cone would not break when lying on the smaller end, but broke when the cone was turned and the same plate placed on the larger end.[349] See Figure 35, *Fig 29.* According to Vream, this experiment showed that the total pressure of the atmosphere is proportional to the surface it acts on, but he gave no figures or calculations.

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[343] Hauksbee and Hodgson (1708) 3.
[344] Vream (1717), exp. 11, 12.
[345] This was the same principle as in Hauksbee's air-pump valves. See Chapter 1.
[346] The wire-cage was used for limiting the spread of glass fragments. See Figure 35, *Fig 8, 9 and 12.*
[347] Hauksbee and Hodgson (1708), 3.
[348] Vream (1717), exp. 20.
[349] Ibid, exp. 48.

Hauksbee/Hodgson and Desaguliers had other versions of the 'bottle experiments'. They described tests using round bottles instead of flat-sided ones, as well as other experiments where condensed air was used. In experiments where square phials would break, either from inside or outside pressure, a round bottle would normally hold. The square/round bottle experiment was tried in many variations, and with several pressure combinations. Hauksbee and Hodgson were also able to break round bottles containing atmospheric air, despite their form, using compressed air on the outside,[350] while Desaguliers described how round bottles would bear to be exhausted, but not to be injected with compressed air.[351]

The required equipment for these experiments included square and round bottles; pieces of flat glass; an open-ended, truncated brass cone; wire cages; and water-filled vessels for increasing the effects. See *Fig 8, 9, 12* in Figure 35, and Figure 39.[352] Hauksbee's influence on these gadgets is also evident here. Vream's one-way valve was in principle similar to Hauksbee's crucial air-pump valves, made up of a small piece of bladder. The air could be sucked out through this device as the bladder became lifted up a little by air streaming out, but when the pressure on the outside got greater than on the inside, the bladder tightened to the opening, and the valve became closed.[353] The small bladder-valve, the cages and the brass-cone were maybe the only equipment made especially for these experiments.

A thorough examination of the syllabi shows that air-pump experiments with glass bottles were used for demonstrations of various issues. When the *spring* of the air (elasticity) was to be shown, they removed the air from the *outside* of the bottles, but when the *pressure* of the air was shown, they removed it from the *inside*. To break a bottle from the inside requires of course a pressure on the inner surfaces, but to do it this way, they showed that this pressure had to come from the spring that existed in common air. When they wanted to demonstrate that the surrounding common air was exerting a pressure on all surfaces (omni-directional), they simply removed the pressure on the other side (here: the inside) of the glass wall. The basic



**Figure 39.** Thin-walled phials (ca 1750). *Pe&P Science* (1993), 282.

[350] Hauksbee and Hodgson (1708), 2.
[351] Desaguliers (1717), 39, 40.
[352] No information on the size and wall-thickness of the bottles were given, and none from this period could be found in museums. In the 'King George III Collection' there are several thin-walled, round and square phials from c. 1760. See: Morton and Wess (1993), 282.
[353] Vream (1717), exp. 21.

properties of common air like weight, spring and pressure had earlier been highly debated. The true nature of the invisible air could only be revealed by artificial means. However, while the phial-breaking could demonstrate basic properties of air, it did not quantify them. Neither did the cone experiment, but in this case it was possible to see that the total pressure increased as the surface increased.

When Hauksbee/Hodgson and Desaguliers investigated the difference in behaviour between round and square bottles under pressure, they were, strictly speaking, not doing pneumatics, but *mechanics*. To show that a round surface could bear more weight than a flat one by using breakable glass could have a pedagogical value, even if the phenomenon itself had to be well-known from building practice. (That a curved arc could sustain more weight than a straight beam of comparable length). Desaguliers explained this fact by saying that the air's pressure is less resisted by the sides of the square bottles, and that round glasses and arcs sustain one another, and that the pressure upon them are uniform.[354] In 1717, Desaguliers described that round glass bottles would sustain a higher pressure from the outside than from the inside. To show this, he first exhausted the flasks by the air-pump. He didn't give the value of the inside pressure, but if we assume it to be within a few percent of normal air, he achieved a pressure difference between the inside and the outside of about one atmosphere if the bottle itself was surrounded by common air. The bottle did not break, showing that this curved glass surfaces could sustain a pressure difference of one atmosphere from the outside. When the highest pressure was applied on the inside, however, things changed. Again the bottle was kept in common air, but now injected with compressed air. The bottle would break, he says, but does not mention the amount of extra air inside. Only if the bottle was burst by a pressure difference less than in the first experiment, could he say that a round bottle would stand a higher pressure from the outside than from the inside. Without knowing the pressure difference over the glass walls, it was, strictly speaking, not possible to reach this conclusion. Desaguliers gave more details in his main work of 1744. There he said that a round bottle might sustain 10 atmospheres acting from the outside, but hardly stand a pressure of 3 or 4 atmospheres from the inside, since 'the parts of the glass then do not support each other like an arc'.[355]

These experiments were not performed for investigating the properties of air, but to demonstrate the mechanical properties of different structures, and the strength of glass. This is a clear example of how the air-pump became used as a tool for demonstrating 'non-pneumatic' effects, in this case traditional mechanics.

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[354] Desaguliers (1717), 40.
[355] Desaguliers (1744), 395.

### 4.2.3 Explosions

Ignition of gunpowder in vacuum was another exciting demonstration in the public lectures. The phenomenon had been studied by experimental philosophers earlier, among them Robert Boyle, John Mayow (1641-1679), and Robert Hooke (1635-1703). Gunpowder burns in vacuum, but does not explode like in open air. Mayow had developed the concept of 'nitro-aerial spirits' in the 1660s, denoting a substance common to air and niter in his attempts to understand combustion. Hooke used similar concepts.[356] Niter (saltpeter or potassium nitrate) is the element in gunpowder that burns in vacuum; the two others, sulphur and charcoal do not.

However, neither Hauksbee nor the other lecturers referred to 'nitro-aerial spirits' in the course-descriptions.[357] In the Hauksbee/Hodgson syllabus from 1706, we find a heading about the 'firing of gunpowder, Aurum Fulminans, and other inflammable matter in vacuum.[358] They gave no more details, except that it was fired on a 'candent' (incandescent) iron.[359] Hauksbee Junior and Whiston had these experiments on the agenda as well, shown among 'the more hidden' properties of air, together with demonstrations of the influence of air on sound and fire, and the effects of burnt air upon the life of animals.[360] No more details of the experiment were given, but a technical description of the actual apparatus was supplied. Both Vream and Desaguliers (1717) had gunpowder explosions on the programme. In the 'miscellaneous' section, Vream gave a series of practical instructions and advices on how to perform such demonstrations,[361] while Desaguliers stated that gunpowder 'fires only corn by corn' in a vacuum.[362] Like in the two previous sections, the air-pump was more or less 'invisible' in these tests, acting as a trivial tool only, as well as that the phenomenon was used to explain mechanical properties of air.

The main contrivance used in these experiments was a specially-made receiver, first described by Hauksbee the elder in his book and articles, and later by Hauksbee the younger as well as Vream, who both gave a picture of it. See Figure 35, *Fig. 23*. A reading of the texts gives us a reasonable understanding of how it worked, even though no cross-section or principle illustration is given. It was a small receiver, which contained a mechanism that could let a distinct amount of gunpowder fall onto a glowing iron every time a thick wire was pulled up and pushed down again. Placed upon the pump-plate, the receiver could be evacuated and possible pressure variations could be monitored by the in-built pump-barometer. As we understand from the text, the gunpowder was lying in a depression in a piece of cork in the neck of the receiver. The wire had a hole like an

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[356] T. Hankins: *Science and the Enlightenment* (Cambridge, 1985), 93.
[357] Hauksbee just mentioned 'Nitro-aerial spirits' briefly in his book. *PME* (1719), 109.
[358] Aurum Fulminans was an explosive substance made from gold dissolved in Aqua Regia. See: *Boyle's Works*. vii, 93. See also See Harris (1737), under 'Aurum Fulminans'.
[359] Hauksbee and Hodgson (1708), 4.
[360] Hauksbee and Whiston (1714), 3.
[361] Vream (1717), exp. 36.
[362] Desaguliers (1717), 39.

eye of a needle, and by pulling it upwards, the eye would push into the gunpowder and become filled, maybe by a little tapping on the neck. When it was pushed down again, and the eye became exposed to the vacuum, the gunpowder would fall out and down onto the red-hot iron. Since the eye could only be filled with the same amount of gunpowder every time, the same quantity would drop whenever the wire was pushed down. A cross-section of the device, reconstructed from the original texts and illustrations, is given in Figure 40.[363] The stopper at the lower end of the wire is not mentioned in the text, but is supposed to prevent the wire from being accidentally pulled too high and thus letting all the gunpowder fall down on the red-hot piece at once.

Hauksbee and Hodgson were not very specific about their gunpowder experiment in their lecture description, but one effect that they might have shown there is sufficiently described in Hauksbee's book. By igniting certain quantities of gunpowder in a vacuum, Hauksbee observed that a pressure-increase took place, as indicated by the mercury-gauge on the pump. He also noted that the pressure decreased when the set-up cooled down. These pressure changes must have been easily observable for the lecture audience by watching the barometer. Hauksbee wrote that the increase in pressure that took place inside the special receiver was due to 'factitious' air, produced by the burning gunpowder.[364] He was interested in what he called the 'qualities' of this contrived air, and concluded that one quality was that it expanded and contracted by temperature-changes just as normal air. When the gunpowder receiver, still placed on the pump-plate, had cooled down, Hauksbee was able to change the pressure by simply laying his hand on the glass and therefore increase the temperature, an effect that could be observed by the barometer.

From the description of the gunpowder-receiver by Hauksbee Junior and Whiston, it becomes clear that when gunpowder falls upon the hot iron, the explosion produces a flame and factitious air. Compared to gunpowder explosions in open air, this one produced very little sound, however. The reason they gave was 'the absence of conveying air' and, for example, not the fact that the firings in vacuum were quite different and smaller than those taking place normally. In this case the gunpowder experiment functioned as an alternative to the sound-in-a-vacuum experiment; these experiments were scheduled in the same lecture.[365]

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[363] The fact the dispenser could let a certain quantity of gunpowder (1.2 grain or 80 milligrams) drop onto the red-hot iron every time, tells us that this instrument was intended not only for demonstrating interesting effects, but also for careful investigations (research) where the exact amount of gunpowder was a parameter.

[364] The expression 'factitious air' was used in contrast to the 'common air', which was removed by the air-pump. This is an early recognition of the existence of other kinds of 'airs' beside the common one. See F. Hauksbee, 'Experiments concerning the Effects of Air Pass'd through Red Hot Mettals, &c', *PT*, vol. 27 (1710), 200.

[365] Hauksbee and Whiston (1714), 3.

However, Vream and Desaguliers underlined that gunpowder fired 'corn by corn' on the red-hot iron. Vream did not offer any explanation of the phenomenon, but Desaguliers stated that the reason why gunpowder exploded in common air was the resistance of the air. This indicates that their explanations of the limited explosions in a vacuum were connected with the lack of air, or to be more accurate, the absence of a surrounding air-pressure. It must have been well known that the effects of exploding gun-powder could be much stronger when the explosion took place in a closed space, such as in a shell which made resistance to movements, than by simply igniting the powder in open air. Their logic is therefore clear: when the air, which had weight and pressure and a resistance to movements, was taken away by an air-pump, the effects of an explosion would be less than one in common air. Hauksbee concluded that explosions of like quantities of gunpowder should be greater when resisted by air, than in a vacuum where nothing seems to hinder it.[366] The use of the expression 'corn by corn' can also be understood, as it points to another characteristic of the phenomenon. When gunpowder exploded in open air, it was with flames, noise and smoke, and an observer had no chance to see what happened with the distinct particles. In a vacuum, however, nothing was heard, but a smoke could be seen from the burning corns and a pressure-increase could be detected.

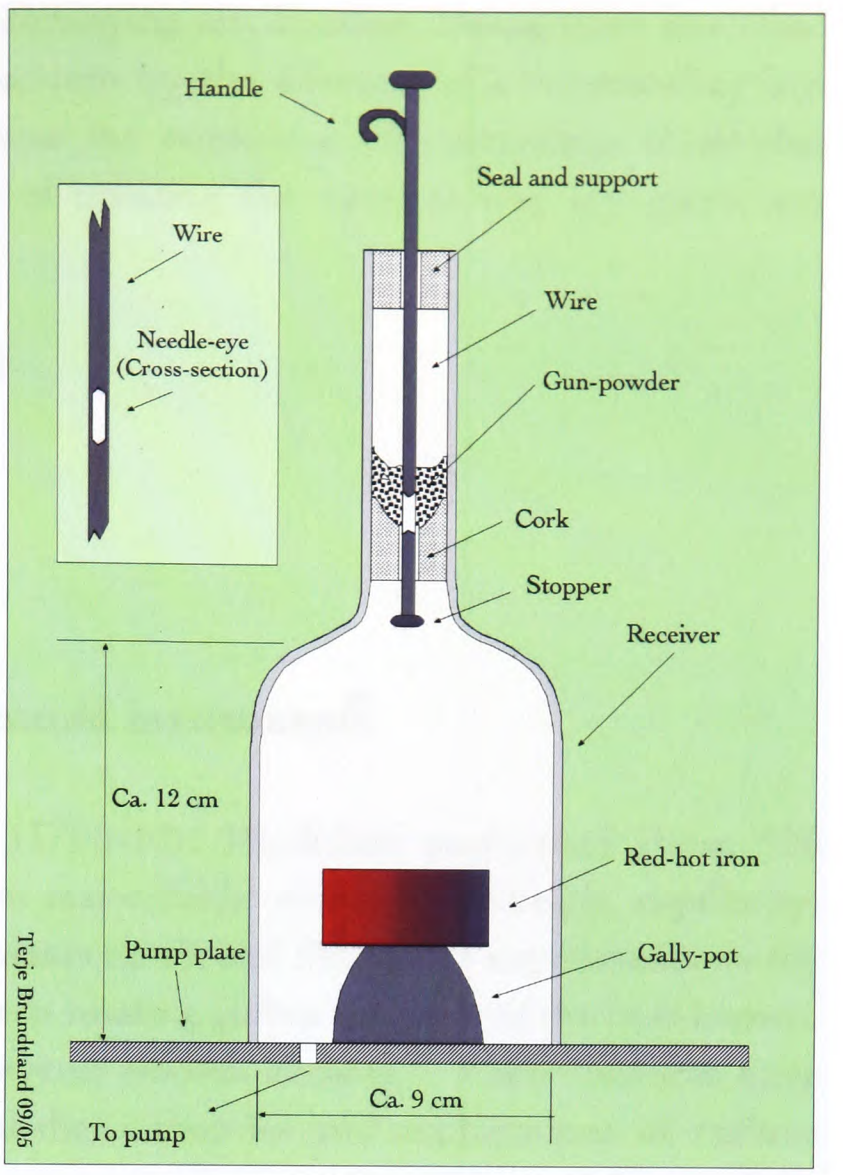



**Figure 40.** The gunpowder-receiver.

These actors explained the actions of gunpowder in vacuum by physical properties of air, and not by what we would call chemical ones. When Hauksbee studied the qualities of factitious air produced by gunpowder, he studied in fact the expansion and contraction of air (gases) caused by temperature changes. And when Hauksbee the younger and Whiston explained why no sound was heard from gunpowder igniting in a vacuum, they used the same argument as in the bell-

[366] F. Hauksbee, 'An Account of an Experiment Made Decemb. the 26th, 1704', *PT*, vol. 24 (1705), 1809.

experiment: because there was no conveying air. Further, Desaguliers described the lack of real explosions in a vacuum by the absence of a surrounding air-pressure. According to them, it was the *mechanical* characteristics of air that counted. The pump, or the tasks of creating the vacuum was not given any attention.

## 4.3 Separated instruments

During a period of ten years (1703-13), Hauksbee performed about 120 different experiment on five different major fields: electricity and light, capillarity, sound, life experiments, and experiments on air and fluids. His experiments on the production of light and electricity from rotating globes are some of the best-known, and have been commented on by several modern authors.[367] Their concerns have primarily been to understand Hauksbee's theories and explanations of various phenomena; I will use these experiments, as well as one in optics, to understand the status of the air-pump, the external instrumentation, and the extended vacuum concept.

One necessary condition for the shift in attention from the air-pump to the additional apparatus was the fact that the pump had reached a stage of reliability and functionality where it neither represented a problem, nor was a time-consuming device. It had become black-boxed, and achieved social acceptance and agreement concerning its functions. However, the development of pump appurtenances continued after this process had ended. In the following, I argue that Hauksbee's experiments with the pump created new accessories, which in turn developed into discrete instruments that worked separated from the pump and possessed functions of their own. I also show how this led to 'vacuum' becoming a parameter.

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[367] G. Freudenthal, 'Electricity Between Chemistry and Physics: The Simultaneous Itineraries of Francis Hauksbee, Samuel Wall, and Pierre Polinière', *Historical Studies in the Physical Sciences*, Vol. 11(1981), 203-29;
R. W. Home, 'Francis Hauksbee's theory of Electricity' in *Archive for History of Exact Sciences*, 4.10 (1967), 203-217;
J. Heilbron, *Electricity in the 17th and 18th centuries: A study of early Modern physics* (Berkeley, 1979), 229-39;
W. Hackmann, *Electricity from Glass* (Alphen and der Rijn, 1978), 29-39.

### 4.3.1 Globes and Cylinders

Hauksbee's experiments with rotating globes and cylinder can be traced back to his early demonstrations of barometric light. This was an issue at his first demonstration at the Royal Society in December 1703,[368] and a corresponding phenomenon was accounted for in an article in the *Philosophical Transactions* in September 1705. There he described how he was able to create a glow in the column of the in-built barometer of the pump by forcing the mercury to move up and down by means of varying the pressure in the receiver.[369] His next step was to create similar light-phenomena by letting mercury droplets touch and slide down along glass surfaces in a vacuum, inside specially-made receivers that were placed upon the pump plate and exhausted there (Figure 32).[370] Inspired by the light that he achieved from friction between mercury and glass, his next development in the field was the large set-up for rubbing different substances against each other in vacuum (Figure 16).[371] Also here he obtained various sorts of lights. The last two experiments represent air-pump experiments of the third stage, characterised by special receivers.

Hauksbee's next move was an important one. While the first barometric light was made, it was obtained *inside* the barometer attached to the pump; when he obtained light from mercury droplets or by rubbing of various substances, it took place in the specialised receivers placed *upon* the pump. He now continued to produce various phenomena of light and electricity with pieces of apparatus that were separated and located *away* from the air-pump. His first experiment in this series was made with a vertically-mounted globe, exhausted by the double-barrelled pump: the globe was then closed off, removed, and fixed to a stand where it was turned by the large wheel.[372] The vacuum created by the air-pump was thus made transportable, and dislocated from the pump. The next development was a 'new contrivance', a separate and freestanding machine for supporting and rotating horizontally-mounted glass-cylinders and globes.[373] This machine represented a major step in Hauksbee's experimental activity regarding light and electricity. See Figure 36.[374] When used for studies in electricity, which in this context meant the attraction and repulsion of small objects, he normally used un-exhausted globes, and detected the effects by various arrangements of wool-threads. Later he built yet another machine, that could rotate two cylinders, one inside the other. See Figure 41. A scheme showing the different stages of the development towards these 'large

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[368] The 'Journal Book' JBC 10 (1702-1714), 55.
[369] F. Hauksbee, 'Several Experiments on the Mercurial Phosphorus', *PT*, vol. 24 (1705), 2131.
[370] Ibid, 2129-35.
[371] F. Hauksbee, 'Several Experiments on the Attrition of Bodies in Vacuo', *PT*, vol. 24 (1705), 2165-74.
[372] F. Hauksbee, 'An Account of an Experiment Made before the Royal Society', *PT*, vol. 25 (1707), 2277-82.
[373] F. Hauksbee, 'An Account of an Experiment (...) Touching the Extraordinary Electricity of Glass', *PT*, vol. 25 (1707), 2332-5.
[374] *PME* (1719), Tab VII.

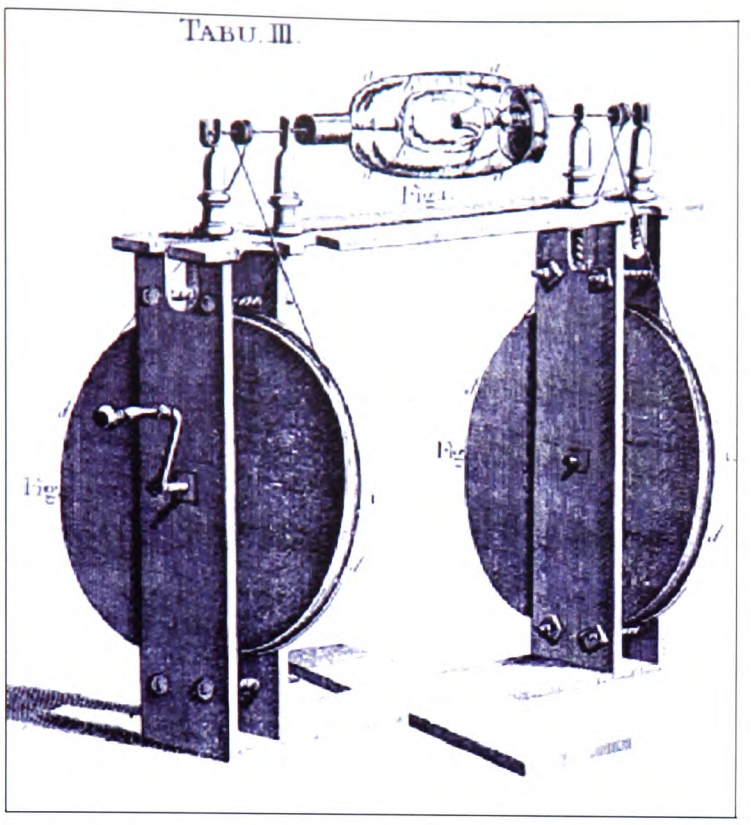



**Figure 41.** Hauksbee's machine for giving rotation to two cylinders, one inside the other (1707). The inner cylinder could be evacuated. A light phenomenon occurred in the inner, when the outer became rubbed From *PME* (1719).

air-pump accessories' is given in Figure 42. This development paralleled the development of the different stages of the air-pump.

Moreover, I have made a replica of the rotating globe machine. See Figure 43. For that purpose I had to peruse the texts from a third point of view, not looking for Hauksbee's theories or experimental practice, but for details of construction. In the following, I will augment traditional sources with some of my own experiences with the machine. A technical description of it and an account of the replication work are given in the Appendix.

A study of Hauksbee's texts on the globe-experiments makes it clear that he devoted little space to the air-pump. In the first experiments, he normally mentioned that the globe became evacuated, closed off and transferred from the pump to the rotating machine, and later he did not mention the pump at all. In the discussions that followed the apparatus-descriptions, the air-pump was never mentioned, but Hauksbee now and then referred to the 'exhausted globe'. One reason for so little emphasis on such an important instrument must have been the result of the black-boxing process. At this stage, Hauksbee could have expected his readers to be familiar with the device so that information on its function and application would have been superfluous. This might well have been the case, and corresponds with his note from 1709 (given in the opening of this chapter), where he said he would not 'take any notice' of the pump, but only of the experiments that he made with it.[375]

Another possible reason for this shift in emphasis, from the basic to the special instrument (from the air-pump to the globe), was that Hauksbee adjusted the text to fit with the developing standards for philosophical articles. Indeed, I suggest that Hauksbee had a part to play in the creation of these standards, and that his accounts of these experiments helped to shape the writing style of such texts. In the beginning, most articles in the *Philosophical Transactions*, the oldest scientific journal in English (running from 1667), were written along a 'recipe' scheme with detailed instructions for creating marvellous effects or making useful things. An additional characteristic was short accounts of observations of various phenomena, for

[375] *PME* (1719), 21.

example uncommon weather and strange plants and animals. This tradition seems to have ended with the last volumes of the seventeenth century, where the emphasis moved to the instruments and the phenomena they showed. Texts became more geared to novelties, results and explanations, and experiments became a way to test hypothesis and solve debates.[376] The accounts also ceased to be self-contained in this period. Hauksbee, for example, did not explain everything; he just referred to previous articles for reliable accounts on instruments and procedures.

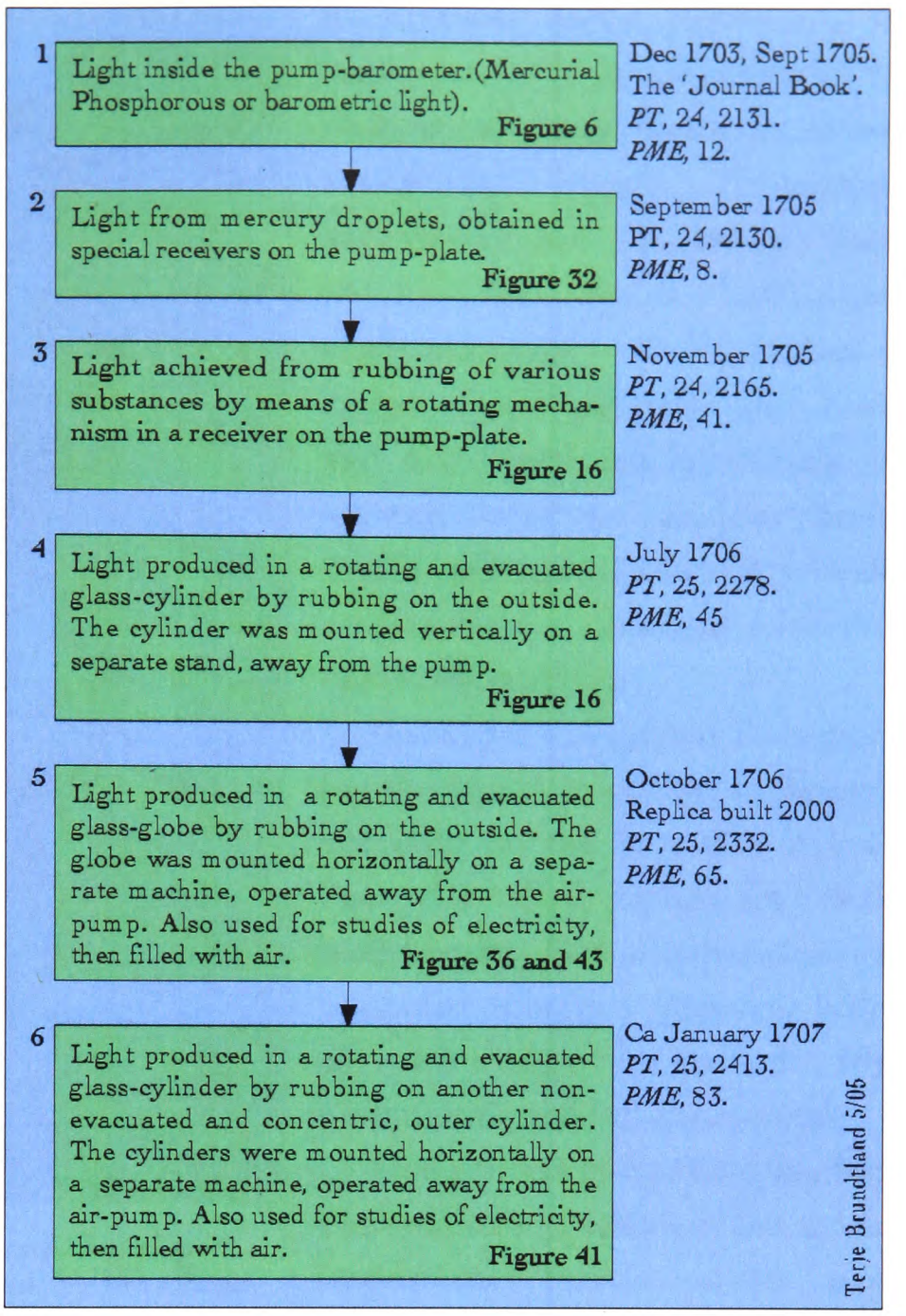



**Figure 42.** The development of Hauksbee's air-pump-accessories his first mercurial light made in the barometer of the pump, through phenomena in specialised receivers on the pump-plate, to effects created in discrete instruments that were operated independent of the pump. This development paralleled the development of the different stages of the air-pump.

Nor was Hauksbee simply following where other more significant figures led the way. The most productive author in the first quarter of the eighteenth century was in fact none other than Hauksbee himself, with fifty articles during a period of ten years.[377] Desaguliers was a productive contributor to the *Philosophical Transactions* as well, and it has been suggested that he and Hauksbee might have influenced the style of scientific articles themselves.[378] We can take Hauksbee's article about the rotating globe as an example to study the writing process. It is an account about testing his theory on luminous matter and electricity, and includes descriptions of apparatus,

[376] C. Bazerman, *Shaping Written Knowledge* (Madison, Wisconsin, 1988), 67.
[377] For a discussion on authors and content in the *Philosophical Transactions* in this period, see: Heilbron (1983), 40-51.
[378] Bazerman (1988), 67.

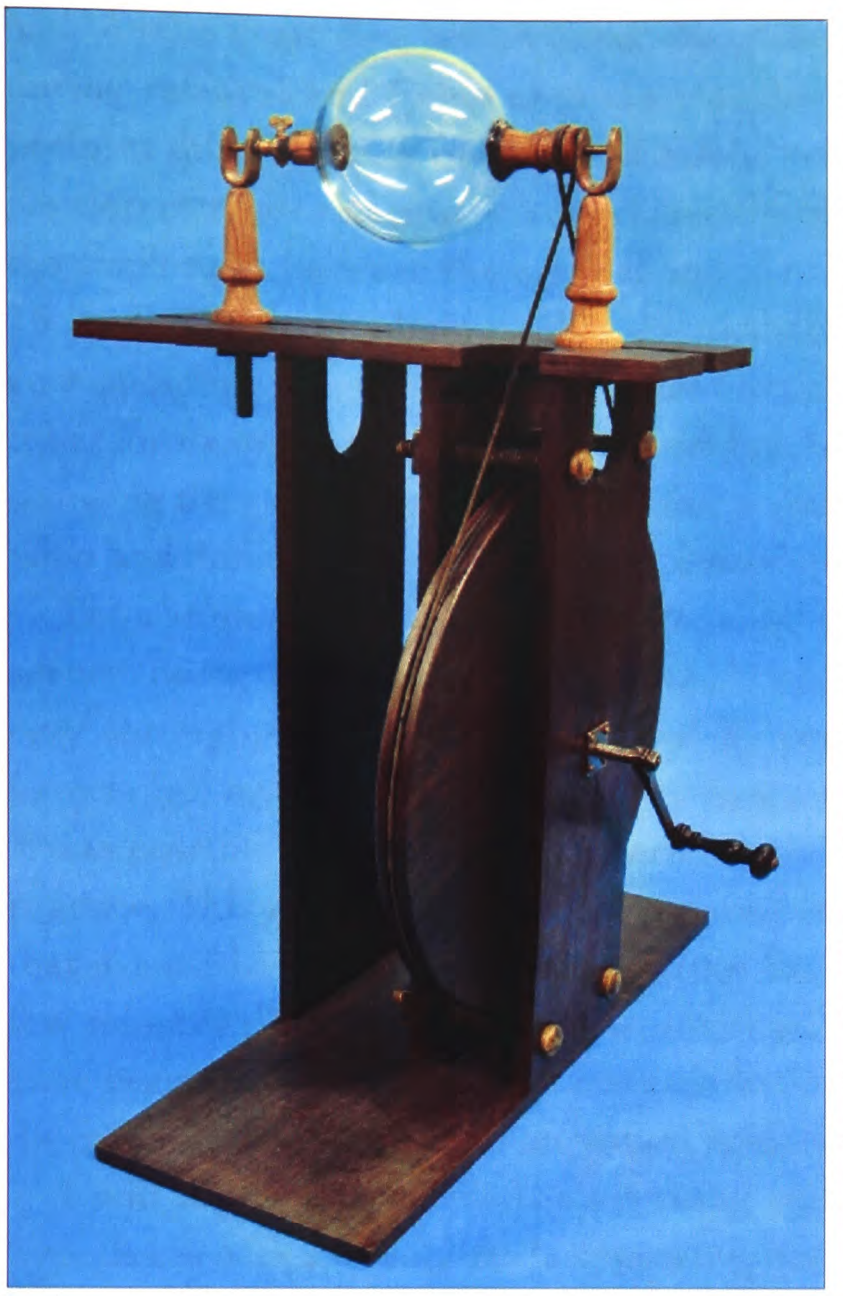


**Figure 43.** Replica of Hauksbee's rotating globe for studies of light and electricity, built by the author. (Tromsø and Oxford 2000). Compare with Figure 36. Photo: University of Oxford.

illustrations, and arguments.[379] A survey on these issues is helpful to understand the development of the air-pump and air-pump accessories, and Hauksbee's role in it. To obtain sufficient understanding of Hauksbee's experimental practice and how this was expressed in writing, it seemed vital to consider both traditional textual sources as well as experiences obtained with my replicated machine.

Hauksbee's apparent disregard for the pump might be explained not only by the fact that it had been described earlier and was well known, but also because its operation required relatively little of the time required for undertaking the full experiment.

This proved to be the case, but the reworking revealed that other important issues were not mentioned at all.[380] I will in the following give one example, and show that the practice of leaving out important but tedious details of an experiment-account was present already with Hauksbee. What required more time and was more difficult than pumping, but never found its way to the *Philosophical Transactions*, was the process of removing the globe from the machine, placing it in a secure rest, connecting it to the pump by a hose, and finally putting it back again after pumping. My own tests showed this to be a difficult and time-consuming task, especially in the beginning. I

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[379] As an example on Hauksbee's attitude to the use of experiments, see: F. Hauksbee, 'An Account of an Experiment', *PT*, vol. 25 (1707), 2415. In this article, concerning characteristics of the air- pressure, he wrote that: 'Since the greatest Satisfaction and Demonstrations that can be given for the Credit of any Hypothesis, is, That the Experiments made to prove the same, agree with it in all respects, without force'.

[380] The time for evacuating the globes could not have been very long in itself. Calculation based on pumping times given in Chapter 3 points to a figure of about one minute for a 9" globe.[380] I used a modern air-pump (a 'vacuum-pump') to evacuate a similar globe, which took the pressure down in a fraction of a minute. However, this was the time required for the actual pumping, from I switched the pump on until I switched it off. For Hauksbee, it would have been the period when he pushed and pulled the crank back and forth for evacuating the globe.

had to take great care not to break the globe, which was particularly vulnerable during removal and fixing onto the machine (see the Appendix). To be able to perform this operation quickly and safely, with onlookers watching me, I had to develop routines and practice to achieve the necessary skills and confidence. From the similarities between the original and the replicated machines (compare Figure 36 and 43), it is obvious that Hauksbee had to work himself through a corresponding process. He could either have connected the globe to the pump by a tube, for example like the one he used for the mercury globe (see above), or by screwing the globe-stopcock directly to the pump. In both cases it must have been a tense and difficult task for him, being concerned not breaking the glass.

The nature of the work itself could partly have been the reason for Hauksbee's silence. Some of it was of a kind that could not be expressed directly in writing, but only through experience and learned by practice. I had to achieve such 'tacit knowledge' myself to be able to do my demonstrations efficiently, and learned that it was possible to reduce the time needed for this operation considerably through practice. This must also have been the case with Hauksbee, and from this follows that it must have been possible to reduce the time dealing with the air-pump to a few minutes. Based on my experiences, I would estimate the whole operation to have normally taken about 3-4 minutes for Hauksbee. However, he chose to omit descriptions of this short but important operation.

I will argue that Hauksbee's writing style, with its emphasis on testing of hypotheses with specially-made apparatus, but also leaving out descriptions of well-known instruments and uninteresting experimental practice, was not because he had to follow a set of conventions. This shift in emphasis, from the general and all-inclusive account to the narrow and specialized report, was a novel way of writing that arose from his own particular situation. From this point of view, it is more correct to say that Hauksbee created a style than followed an existing one. This must have been caused by the black-boxed air-pump and the actual experiments, as well as the growing scientific community which included the Royal Society and the readers of the *Transactions*. In this perspective we can see the importance of these experiments in an even broader view, as they also contributed in shaping the scientific article as a literary genre.[381]

Moreover, while reworking some Hauksbee's experiments, it became clear to me that the evacuation procedure could only have occupied a small portion of the time used for the whole undertaking. When I had mastered the procedure of removing, pumping and fixing the globe to the machine, I systematically tried to follow parts of his accounts about production of light. This required a considerable amount of

[381] I see here a parallel with Boyle's efforts in developing a technique for spreading knowledge obtained experimentally by air-pumps. Hauksbee's contribution can be described as part of a second phase in this development. See Shapin and Schaffer (1985), 25. A full discussion of the topic falls outside the scope of this thesis.

time, and each phenomenon that I tried to recreate needed a much longer time than the exhausting and the fixing of the globe. The situation could not have been much different for Hauksbee. The inventiveness and imagination he demonstrated in these experiments must have had its equivalence in hard and time-consuming labour.

The whole point here is that during experiments with exhausted, rotating globes and cylinders, the air-pump was not focused upon very much. It represented the necessary starting point by setting an important parameter, but except for that, it was not in use. Trying out rubbing the globe with different materials, stopping for changing the pressure by letting in air through the stopcock, starting over again and making new observations, all this must have taken time. If onlookers were present, the discussions that naturally followed about the obtained phenomena would definitely have lengthened the experiments. For me, it is not uncommon to finish off a demonstration after an hour's work, making systematic experiments with it takes even longer time.

While Hauksbee's studies of light and electricity resulted in new instruments and a new writing style, it also led to a new use of the term 'vacuum'. According to the various stages in the development of the air-pump proposed above, the rubbing or attrition of various materials in vacuum should fall into the third class, which was characterised by external equipment and specially-made receivers. Following the same scheme, experiments on light and electricity with evacuated glass globes and cylinder fall in the fourth group. This corresponds with the change that took place when air-pump accessories were moved away from the pump and became turned into discrete instruments. Parallel to this, the role of the vacuum also changed, more or less following the distinction between these stages of the air-pump.

In the beginning, Hauksbee had used the term 'in Vacuo' ('in Vacuo Boyliano' in the advertisements) to describe the condition inside the receiver where the experiments took place. This is easily observed from a reading of his accounts on the experiments on barometric light, on the chafing experiments ('the attrition of bodies'), as well as those concerning capillary phenomena. However, this term is not common in the listing of the experiments with the rotating glass-globe and cylinders. In the headings as well as the text, he used expressions like 'a glass globe *exhausted of its air*', and *'degree of rarefaction of the air in the globe'*, together with *'the globe...replenished with air'*, and *'the same quantity of air was readmitted'*. [382] In the discussion, Hauksbee now and then compared the results from the globe experiments with his previous experiments on mercurial phosphorus (barometric light). Those experiments had been performed *in vacuo* and in open air, however, while the present one were made by an *exhausted* globe.

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[382] See For example *PME*, 45, 47, 48.

In spite of this, there is nothing that suggests that Hauksbee thought of the vacuum in the globes as, in principle, different from the vacuum that he created in the receivers, but as more of a different application. If I should try to distinguish between them: vacuum applied in experiments with pumps of the three first stages can be described as an artificial *environment,* normally referred to as a 'vacuum' or 'in vacuo'. The vacuum in the globe (and also in the hollow prism, see below) can be described as a *parameter,* and mostly referred to as 'exhausted of air,' etc.

I will go a little deeper into the last issue. By studying the globe-experiment, it becomes clear that Hauksbee set up various experimental conditions, as well as that he registered the behaviour and responses from it. (This is called 'input and output data' in modern terms). A study of the texts make us able to list a series of actions and conditions that he arranged to undertake the experiments, for example rotation and speed (surface velocity of the globe); the movements of the hands and fingers on the glass-surface; dryness of the hands; moisture on the glass and in the ambient air; the temperature of the glass; different rubbing materials such as naked hands, white sheep-skin, or a neck-cloth, as well as the degree of exhaustion of air inside the globe. A corresponding list of output-results from the experiments can also be made, like shapes, colours and forms of the light inside as well as outside the globe, the intensity of this light, the wheezing sound that accompanied the outside sparks, the rattling noise of the machine itself, as well as the behaviour of the wool-threads that Hauksbee used for observing electricity on the glass or in its close vicinity. See Table 3, Figure 44 and Figure 45.

Among this array of input and output conditions, some of them constant and some variable, we find *air* inside the globe in various degrees of rarefaction. During the experiments Hauksbee could vary the amount of air inside the globe, starting with a fully evacuated globe and then let air leak into it by more or less controlled operations of the stopcock. The impression received by reading these texts is that the rarity of air in the globe was a necessary variable in the experiment, but except for that, he did not pay much attention to it. For example he never gave any accurate values of the pressure during an experiment. What happened was in fact that vacuum was 'added' to the

| **'Input' parameters** |
|---|
| Rotation |
| Surface velocity |
| Air, from atmospheric pressure to vacuum |
| Movements of hands and fingers |
| Dryness of hands |
| Dryness of glass |
| Humidity of ambient air |
| Various rubbing materials |
| **'Output' parameters** |
| Inside shapes and forms of the light |
| Colour of the light (the luminous matter) |
| Intensity of the light |
| Length of outside sparks |
| Colour of outside sparks |
| Sound accompanying outside sparks |
| Rattling noise from the machine |
| Behaviour of the wool-threads |

**Table 3.** 'Input' and 'Output' parameter of the globe experiment.

experiment by exhausting the globe by the pump. In this way vacuum had been downgraded from its status of a special environment in the receiver, and made into just one of a series of necessary conditions for a successful experiment. In fact, this is maybe best illustrated by an expression found in two headings in *PME*, where Hauksbee himself described some globe experiments to be made under the 'Circumstances of Attrition *and* a vacuum'.[383] Clearly, with these trials, vacuum had developed into a parameter, one used among several others in experiments on natural philosophy.



**Figure 44.** Inputting rotation and rubbing. Where is the air-pump? (Oxford, Sept. 2002). Photo: University of Oxford.



**Figure 45.** One output parameter: luminous matter in the reconstructed globe. 30 sec. Exposure. (Oxford, Sept. 2002). Photo: University of Oxford.

[383] *PME*, 268, 298.

### 4.3.2 The prism

This view is also supported by the account of another experiment. I will in the following show how the term 'vacuum' developed towards the same meaning as described above, and how the air-pump became just a 'supplier' of it, but along a quite different line. In Hauksbee's book, *Physico Mechanical Experiments,* there is a chapter called 'Experiments concerning the refraction of the air'.[384] There he described the construction and use of an apparatus for measurements of refraction indices for vacuum, common air, and pressurized air. This experiment had previously been made at the Royal Society by J. Lowthorp in 1699, and repeated by the French Academy in 1700.[385] Since the results from these two tests didn't agree, Francis Hauksbee was 'ordered' to repeat it, with the guidance of Edmund Halley.

The instruments that Lowthorp and Hauksbee used for this experiment were very different. Even if the aim of the trials were the same, the use of the instruments reveals some of the extended role of air-pumps and the enlarged vacuum-concept that came with Hauksbee's activities. Both arrangements consisted of a hollow glass prism that could be evacuated by an air-pump, and a telescope. The change in position of a distant mark as seen through the telescope and the prism, when the prism was either evacuated or filled with common air, made it possible to calculate refractive indices of vacuum versus air. Lowthorp had used a pumping arrangement where he let the prism become evacuated by an amount of descending mercury, like the pumping method used by Accademia del Cimento. In practice, the bulb on top of the tube had become replaced with a prism. (See Figure 33). The prism, glass tube and mercury reservoirs were all made into one unit, and fixed onto a large table together with the telescope. Following the scheme suggested above, the Lowthorp arrangement fits into the first stage of air-pump instrumentation where the pumping mechanism and the experimental space were one and the same unit.

Not so with Hauksbee, whose contrivance can be used to illustrate quite a different air-pump practice. Hauksbee's prism consisted of two well-polished glass plates cemented into brass sockets; the three other sides were made of brass plates, making up a closed box. It was pumped through a stopcock fixed to the underside of the prism, while the pressure could be monitored by an attached mercury gauge. It could be rotated around its vertical axis, and was mounted on a support together with a 10 ft. telescope, supplied with a 'fine hair'. Hauksbee did not give any illustration of the device himself, but a sketch was given by his nephew, see Figure 46.[386] A close reading of the elder's description makes it clear that the prism-arrangement could easily be removed from its support, and either connected to an

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[384] *PME*, 225. This experiment is one of the few found in *PME* that not is published in the *Philosophical Transactions.*

[385] J. Lowthorp, 'An experiment of the Refraction of the Air', *PT,* vol. 21, (1699), 339-42.

[386] Hauksbee and Whiston (1714). The illustration and description found here match exactly with the elders account.

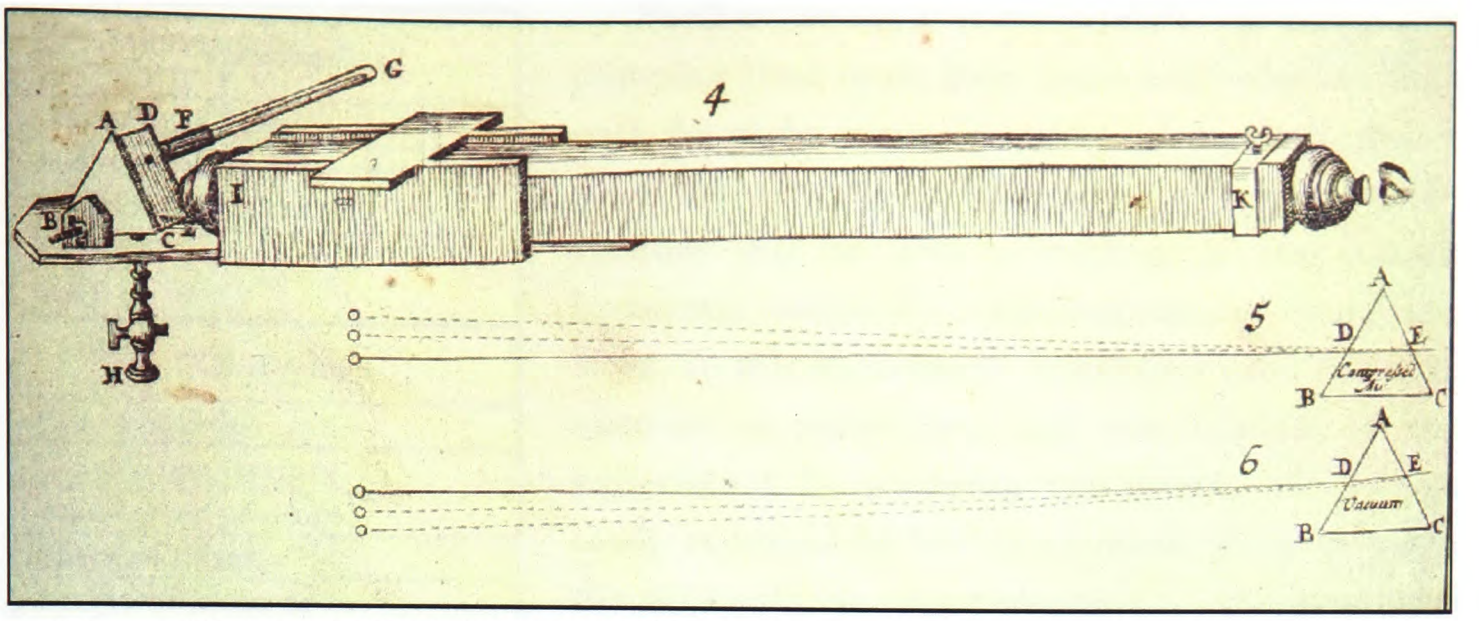



**Figure 46**. Francis Hauksbee's the elder's apparatus for measuring the refraction of airs (1708). *Figure 4*: I-K, telescope; A-C-D-E, prism; B, rotating point; H, stopcock; F-G, barometer. *Figure 5*: Movements of rays by common and compressed air in the prism. *Figure 6*: Movements of rays by common air and vacuum in the prism. From F. Hauksbee and W. Whiston, *A Course of Mechanical, Optical, Hydrostatical and Pneumatical Experiments* (London, 1714). Compare with the prism in Figure 37.

air-pump or condensing engine for evacuation, or filling through the stopcock. Unlike Lowthorp's apparatus, this was a separate and mobile device with its own pressure monitor, and could be brought around according to need. The tests were made by looking at an erect and very distinct object 2588 feet away. (The distance was 51 ft. in Lowthorp's experiment). He made a series of tests with vacuum, common air, and with one and two atmospheres in the prism while recording the change in position of the mark, and made calculations of the refractive indices.

The emphasis that Hauksbee placed on the pump in this experiment, as well as his attitude to the vacuum, become clear from studying the information that he supplied to the readers. He gave a series of data on this experiment like the date, time of the day, outside temperature, the atmospheric pressure, the angle between the glass planes of the prism, the length of the telescope, and the distance to the object.[387] While these issues can be regarded as 'constants' in the experiment, he described a series of 'variables' as well[388]. For example the obliquity of the prism on its axis; the pressure inside it varying from a vacuum to two atmospheres; the change in position of the observed mark on the distant object when the vacuum became replaced with common air, the corresponding change when one or two atmospheres were introduced in the prism by the condensing engine, and so on. When Hauksbee discussed the data obtained with the prism, all these parameters were taken into account, but the vacuum was only one of them. See Table 4. It did not receive much attention.

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[387] It was performed 15 June, 1708, in the morning.

[388] Like above, these data can also be described as 'inputs', and 'outputs'.

| 'Variables' |
|---|
| Obliquity of prism |
| Inside pressure, from two atmospheres to vacuum |
| Changes of position of mark on object |
| **'Constants'** |
| Date and time |
| Outside temperature |
| Ambient air-pressure |
| Shape of prism |
| Length of telescope |
| Distance to object |

**Table 4.** 'Variables' and 'Constants' in the prism experiment.

Further, he never mentioned the air-pump (the pumping time must have been even shorter than with the globe, since the volume was much smaller than the volume of the pump-cylinder itself). Neither did he give a reading of the inbuilt barometer, where the main purpose was to indicate leaks. In this experiment, Hauksbee used the term vacuum as something that was 'added' to the experiment by pumping the prism, which was easily removed by letting common air in through the stopcock. He 'saw through it' in the prism, and it was represented by a number in his calculations. The whole task was not seen as an experiment in pneumatics at all, as he described it as a preparation for a more advanced experiment in astronomy concerning the refraction of light from stars through the Earth's atmosphere.[389] Pneumatics had become a service agency for astronomy.[390]

### 4.3.3 The new vacuum

In spite of differences in both aim and performance for the experiments discussed above, I see three major issues: the practical and the conceptual separation of the instruments and of the vacuum from the air-pump, and pneumatics as a supporting agency for other disciplines.

First, unlike traditional air-pump appurtenances, both the rotating globe and the prism were designed to operate independently and separate from the pump. Even the receiver itself, once one of the two major parts of the pump and the location where crucial experiments, initiating heated debates in science, philosophy and politics had taken place, had here become redundant. The role of the air-pump was now just to exhaust the actual components of the instruments, which then became disconnected and removed. It is also clear that the various globes and rotating mechanisms, as well as the prism, had important functions without being evacuated at all. A vacuum was, for example, not a required condition in those globe-experiments where Hauksbee studied electrical effects of glass on wool-threads,

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[389] *PME*, p. 230.

[390] In Hauksbee and Whiston's course syllabus, this experiment was shown in the 'Optics session'. Hauksbee and Whiston (1714), 2. It is also clear that this became a much used method for measuring the refraction index of air. A similar prism as is found in Museo di Storia della Scienza, Florence, dated to early 19th century. See Figure 35. Ref: W. Hackmann, *Catalogue of Pneumatic, Magnetic and Electrical Instruments* (Florence, 1995), 65.

which he obtained by rubbing and rotating the globes while they were full of common air. The hollow prism was designed to operate with air in an exhausted, common and condensed state inside it. An exhausted prism, however, was no 'must' for this set-up to function, and several measurements were also made without any vacuum or reduced air pressure at all. Vacuum was of course an important element in these tests, but not an absolute necessity for making the instrument work.

Second, the use of instruments that functioned more or less independently of the pump led to a practice where a vacuum only became regarded as one among several other parameters in an experiment. However, this important shift in meaning of the term 'vacuum', from denoting a strange and hostile environment inside the receiver to an operational term, was not so much the results of philosophical reflections and controversies as with earlier practice and developments of the pump. Such issues had been crucial when Boyle moved from his first to his second air-pump. According to *Leviathan and the air-pump,* Boyle's new pump was a response to both technical, operational and ideological objections by Hobbes. The existence of leaks, for example, was not only a technical problem, but also an issue that Hobbes used when rejecting Boyle's claims about new facts revealed by the pump. It had to be dealt with not only for technical reasons, but also for saving the public reputation of Boyle's experimental program.[391] In Boyle's written response to Hobbes, the *Examen,* he claimed that Hobbes had failed as a natural philosopher and used, among others, theological arguments for rejecting his views.[392] Parallel to this, Boyle worked actively with rebuilding the pump. Boyle's move from one type of air-pump (the first stage) to another (the second stage) was a move initiated and accompanied by technical as well as philosophical issues. Philosophical issues, however, were far less pronounced with the step from the third to the fourth stage, exemplified by separating instruments like the rotating globe and prism from the pump, and a new use of the term 'vacuum'. Of course, one reason for Hauksbee to undertake these experiments had been to test a hypothesis on light and electricity, and to clarify the disputed results from the prism-experiments by the French Academy and by Lowthorp. But the change was also something that rose from Hauksbee's construction and practice with the new instruments,[393] and use of a language that was necessary to describe the new phenomena.[394] Nevertheless, the lack of heated philosophical and ideological debates do not make the presented development less important than that initiated by the Boyle/Hobbes controversy. In a broader view, the use of the air-pump, the

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[391] See Shapin and Schaffer (1985), 170.

[392] *Boyle's Work,* iii, 109-88.

[393] Through Hauksbee's instruments, 'vacuum' had in fact become modern in the sense of just denoting a physical parameter, in a way used in physics today.)

[394] There is a long tradition within linguistic philosophy of associating meaning with use. A discussion of this, regarding the new meaning of 'vacuum ' falls, however, outside the scope of this thesis.

external instrumentation, and the 'vacuum' had first now, and not with Boyle, become modern.

A third issue are the signs of pneumatics turning into a supporting agency and a method in other disciplines in this period, represented by the role of the exhausted prism in optics and astronomy, and the globe in early studies of light and electricity.

The shift in attention from the pump to the external equipment can be described as a practical and conceptual separation for both the instruments and the vacuum. The instruments now became applied, and the experiments in question became performed, away from and separate from the pump. The vacuum became used as an entity applied externally, and not necessarily thought of in connection with the pump. This was a result of uses of the black-boxed air-pump; the driving forces being both Hauksbee's own curiosity and ingenuity, as well as demands from the scientific community.

## Conclusion

In this chapter I have shown how the air-pump developed in four stages, from a point where the pump and the receiver were joined in one unit, through separated, open-ended receivers, to a stage where the use of specialized receivers and instruments were typical. Further, I have given examples of air-pump practice on this level by discussing three experiments used in public lectures in London in the period: experiments on animals in vacuum, the breaking of glass by air-pressure, and the igniting of gunpowder in vacuum. I showed that these experiments were not only undertaken as spectacular tests for entertainment purposes, but were used to display important issues like the weight, pressure and spring of the air; as well as the importance of air for conveying sound; and for combustion and explosions, etc.

I have also discussed two experiments with air-pumps on the fourth stage, where the attention moved away from the air-pump towards external and discrete instruments. I showed, by discussing Hauksbee's rotating globe and a prism, how pneumatics had become a service agency for other disciplines, here exemplified by experiments in electricity, optics and astronomy. This will be further developed in Chapter 6.

Another important issue, which has been overlooked by instrument-historians until now, is that these experiments illustrate both a practical and conceptual separation of the instruments and of the vacuum from the pump. It was a practical separation that took place when the emphasis moved away from the pump towards discrete instruments that were applied dislocated from it, and which functioned with and without a vacuum. Parallel to this, vacuum became also something that was used outside and independent of the pump, like a physical parameter.

By this, the pump had become a tool, and the vacuum something that was, paradoxically, thought of like an object.

# Chapter 5
# Public and Private Pneumatics

## Introduction

This chapter is about the air-pump and air-pump demonstrations in public and private settings during the first half of the eighteenth century. It is also about the actors in these undertakings.

One expression used in discussions on natural philosophy in the eighteenth century is 'public and private science', a term that serves as the title of Morton and Wess's book about the George III's collection of scientific instruments.[395] This collection primarily consisted of two sources: a series of simple and utilitarian instruments used by Stephen Demainbray in his public lectures in the middle of the century, and a group of high quality and ornate apparatus, used for entertaining or instructing members of the royal family. The concept of 'public and private science' ranged from a popular audience who paid to attend lectures to an aristocratic elite who owned their own apparatus. Consequently, 'public science' is used to denote teaching, experiments and instruments applied in public lectures, while 'private science' represents rational entertainment as a fashionable pursuit of the upper class.

Morton and Wess have described how both styles derived from activities earlier in the century, emphasising public lecturing and instrument-making. I have shown how one important instrument in these undertakings – Hauksbee's air-pump – came into being. In this chapter I discuss how the area it belonged to, 'pneumatics', developed. I thus let 'public pneumatics' refer to lecturing and demonstrations of pneumatics in the public courses taught by such people as Hauksbee and his

[395] Morton and Wess (1993).

followers.[396] The term 'Private pneumatics' refers similarly to instruments, instructions, and experiments used and undertaken in private homes.

First, I show how the application-area of the air-pump expanded in this period, from being an important philosophical instrument available to a small group only, to becoming a publicly accessible device. Much of this took place within the context of the public lectures. I point specifically to the fact that cupping-related demonstrations had a pedagogical role in explaining basic issues like the weight, pressure and spring of the air to the public.[397]

Hauksbee and his followers were very active in this domain, both as instructors and manufacturers of air-pumps and air-pump accessories. I discuss their instrument-making activity, and show that their production of pneumatic instruments evolved into a profession. I make it clear that Hauksbee and his associates formed a small group of practitioners that was active in London up to about 1745, and who operated separately and independently of the established optical, mathematical and philosophical instrument-makers. In addition to producing air-pumps and other pneumatic instruments, they also supplied cupping and other medical utensils. I denote this group as the 'Pneumaticians'.

Further, I show that a private market for air-pumps, air-pump accessories and technical literature had developed by 1720. The equipment had now become handy, reliable and easily available, factors that facilitated settings like in Joseph Wright's painting, *An Experiment on a bird in the Air Pump* from 1768 (Figure 1).[398]

Finally, I argue that all these activities contributed to transform pneumatics into a recognized field within natural philosophy, to a state with its own accepted methods, terminology, literature, instruments and craftsmen.

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[396] The term 'public science' is also found in the title of L. Stewart's book *The rise of Public Science* (Cambridge, 1992). For a general account of form and content of the public lectures, as well as their importance for disseminating knowledge in the period, see: T. Brundtland, 'Public Lectures on Natural Philosophy in early 18th century London' in: Kunnskap og kunnskapsformidling på 1700-tallet [Knowledge and dissemination of knowledge in the eighteenth century] (Oslo, 2004).

[397] Other experiments are discussed in Chapter 4.

[398] See the *Introduction* about the outer context of this thesis.

## 5.1 Public Pneumatics

Pneumatics was a central theme of the public lectures on natural philosophy that were given in London during the early eighteenth century. The general aspects of these courses are well-described, for example, by Stewart in *The Rise of Public Science* (1992),[399] Morton and Wess in *Public & private science* (1993), and Pumfrey in *Who did the work?* (1995).[400]

The Royal Society was central in these undertakings, with several of its members engaged in transferring the 'New Philosophy' to the population. The first lectures were given in 1705 and quickly became very popular. The time and place for such instruction, as well as the required course syllabi, were announced in newspapers, and the use of printed material and experiments in the lectures themselves was typical. Another important characteristic of these public meetings was the cooperation between the natural philosopher and the instrument-maker.

According to Stewart, the public lectures deserve much credit for the spread of natural philosophy that took place in London during the early eighteenth century. He describes them as important contributions to the intellectual revolution that had started in the seventeenth century and continued throughout the eighteenth, with the early industrialization as a result. They thus played a significant role in promoting Newton's ideas, by allying them with practical Baconianism. Stewart underlines the importance of the Queries in Newton's popular book, the *Opticks* in this process. These conclusions were formed as negative questions, like *'is it not so that...'* and left the subject matter open for discussions, which led the reader towards further thinking and reflection. Stewart argues that the experiments and demonstrations of the lectures served as practical counterparts to the Queries, complementing each other.[401]

However, despite ascribing such a decisive role to these practical undertakings, he does not mention or discuss a single experiment or instrument. Such issues are more closely addressed by Morton and Wess. In contrast to Stewart, they emphasize particularly the technical and practical aspects and their book is an excellent source on the development and content of public lecturing in the period. Nevertheless, the air-pump, which was a central instrument in the lectures, is described only as one among many other devices in this context. It is obvious (with reference to Stewart) that behind the experiments there must have been instruments and behind the instruments there must have been instrument-makers. In contrast to Stewart, I focus (throughout my thesis) on such practical aspects. This adds valuable insight into how natural philosophy was conveyed to the public, and explains how the lecture-demonstrations could become a success in the first

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[399] Stewart (1992), chapter 4.
[400] Pumfrey (1995).
[401] Stewart (1992), 119.

place. Below I will give one selected example, showing how Hauksbee's 'cupping-background' became useful in disseminating natural philosophy.

### 5.1.1 Cupping-related demonstrations

I have in Chapter 1 shown that Hauksbee's reliable air-pumps derived from cupping utensils. The fact that cupping played a crucial role in the technical development of the air-pump has been unknown until now. Here I will show that cupping was important from a didactic point of view as well, now helping to explain pneumatic phenomena to the public. This demonstrates that cupping had an even greater role in spreading natural philosophy than simply being a model for the air-pump. Hauksbee and his followers made and sold cupping utensils throughout their careers, and most of them participated in public lecturing. It is clear from a study of the course syllabuses that cupping utensils and cupping-related experiments were shown in the lectures, and were used as a method to display and explain mainly two issues: the weight, pressure and spring of the air, and the phenomenon of 'air in the flesh'. Cupping, being a popular remedy in healthcare, had thus a pedagogical role in explaining difficult natural-philosophy concepts to the public.

I have in the previous chapter shown how characteristics of the atmosphere and of the air were made comprehensible by experiments on animals and with glass-phials. The various lecture-plans reveal that syringes and cupping glasses were used for such purposes as well. Hauksbee used syringes to demonstrate that it was the pressure of the external air that caused suction.[402] So did his nephew, who used syringes and cupping glasses to demonstrate the 'effects of the weight and the spring of the air'. Hauksbee Junior also supplied an illustration and a description of a 'new sort of cupping glass where the air is sucked out by a syringe' (the elder's model).[403] William Vream, an associate of Hauksbee, used cupping glasses to demonstrate effects of the air's pressure generally,[404] and John Desaguliers (1717) explained why cupping glasses could stick to human skin. When Desaguliers wanted to explain that effects previously attributed to 'nature abhors a vacuum' were in fact owing to the air's pressure, he used, among other instruments, syringes. He also used cupping-glasses of Hauksbee's type in a set-up for demonstrating the general properties of air.[405] The two Hauksbees and Vream described several experiments where the air's pressure was made 'sensible to the touch', this was done by laying the hand on a cylinder placed over the pump opening in order to sense it being pressed onto the rim.[406] In principle, this was the same effect that patients would experience with Hauksbee's cupping method. Also

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[402] Hauksbee and Hodgson (1708).
[403] Hauksbee and Whiston (1714), 3; First Plate, Figure 9, 11.
[404] Vream, (1717), exp. 26.
[405] Desaguliers (1744), 253; plate XXI, *fig 4, 5.*
[406] See Chapter 4, page 181.

Benjamin Worster, who gave public lectures given at the Academy in Little Tower Street in the early 1720s, had cupping and related phenomena on the agenda.[407] My point is that in the setting of the public lectures, the audience was able to experience similar effects to those occurring when they themselves were cupped, a practice many people must have been familiar with at the time. But here it was not for healing purposes, but instead to learn about features of the air from the perspective of natural philosophy.

Another issue that was discussed in the lectures, which also related to the human body, was the phenomenon of 'air in the flesh' and other substances. A question that arose in the seventeenth century was this: If the atmosphere was able to exert a considerable pressure – several tons – on the human body, why was the body not crunched by this force?[408] The answer they gave was simply that air in the pores of the body exerted a similar pressure outwards, and kept equilibrium.[409] By demonstrations undertaken with the air-pump in the public lectures, this phenomenon became now viewable and explained. Vream, for example, showed the audience that air really was trapped in raw flesh, as he was able extract bubbles from a piece that was submerged in a water tank inside an evacuated receiver. He also demonstrated that there was air in various fluids, for example blood. (These phenomena are closely related to cupping – the swelling of the skin in the cupping-glass is caused by the expanding 'air in the flesh').

By using cupping instruments for these purposes, and by establishing a connection between the weight of the atmosphere and the 'air in flesh', the London public learned about properties of the air by issues relevant to body and health. Therefore, in addition to being a model for the air-pump, Hauksbee's cupping instruments served to make pneumatics comprehensible for the public.

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[407] Worster (1722), 151.

[408] This was early connected with the uneasiness that some people experienced during weather changed, while observing variations in the atmospheric pressure by the barometer. See *Boyle's Work* vii, 463.

[409] Harris (1737), under 'Air's Weight'; and Desaguliers (1744), 256.

## 5.2 A new profession

I have in Chapter 1 shown how Hauksbee's production of commercial cupping utensils influenced the development of his air-pumps. I will in this section show how his commercial production of air-pumps and related instruments made air-pump-making into a profession, and that this had great influence on the development of private and public pneumatics. But first I will discuss Hauksbee himself.

Even though I have explained Hauksbee's abilities as an outstanding air-pump maker (he learned from cupping), and given examples of him as an experimenter (Chapter 4), it is still not a trivial matter to describe or categorise him. Who was he? What was his profession? Modern authors have described him as a 'philosophical instrument-maker'[410] but a survey of the relevant literature that I have made shows that this term was not coined in Hauksbee's period. Throughout his career he applied, constructed, manufactured and sold various instruments, but a closer examination shows that the range of commercial instruments was more limited than the diversity of devices that he applied in the public lectures and in his own experiments. So what kind of instrument-maker was he? How did other practitioners recognize him?

In discussions about classification of scientific instruments, it has been pointed out that although certain instruments were described as 'philosophical', for example by Nehemiah Grew in the 1680s,[411] the production of such instruments had no clear craft-location in the period.[412] The traditional notation for craftsmen working with scientific instruments was 'mathematical instrument-maker', while the term 'optical instrument-makers' evolved at the end of the seventeenth century, denoting microscope and telescope-makers. The first known use of the term 'philosophical instruments' in a commercial context occurred in 1726, when the instrument-maker Richard Glynne advertised that he made and sold apparatus for use in 'experimental philosophy'.[413] Further, the category 'philosophical instrument-maker' was not introduced before 1747, and then by an apprentice of Hauksbee Junior, Joseph Hickman.[414] [415] Later, instrument-makers like Benjamin Martin and George Adams announced that they made and sold philosophical, optical and mathematical instruments.[416] Towards the end of the century, there were at least a dozen English instrument-makers who called themselves 'philosophical, optical and

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[410] Clifton (1995), 128.

[411] Grew distinguished between instruments related to natural philosophy, mathematics and mechanics. The air-pumps and the microscope are filed under the first heading, the telescope under the second. See: Grew (1681), 357-79.

[412] Bennett, 'A Viol of Water and a Wedge of Glass', in Gooding(1989), 108.

[413] Warner, D, 'What is a scientific instrument, when did it become one, and why?' *British Journal for the History of Science*, Vol. 23 (1990), 85.

[414] Ibid.

[415] Clifton (1995), 135.

[416] See for example J. Millburn, *Retailer of the Sciences* (London, 1986), the cover illustration.

mathematical' instrument-makers. The question about how Hauksbee identified himself in the landscape of contemporary instrument making has never been subjected to any extensive study. This is what I will do here, discussing Hauksbee's place in the taxonomy. Starting with his instruments, I will show that he, as well as his followers, did not fit into any of the established professional categories of the time.

### 5.2.1 Hauksbee's instruments

Hauksbee's newspaper announcements are a good starting point for understanding his instrument-making activity. These were of two kinds, sale and lecture-advertisements, often running parallel in two different newspapers, *The Post Man* and *The Daily Courant*.[417] The study reveals that Hauksbee was acquainted with a variety of instruments, but manufactured only a few types for sale.

The first series of lectures where Hauksbee participated was arranged by James Hodgson, and started in January 1705.[418] This announcement shows that experiments with air-pumps, condensing engines and hydrostatical utensils were part of the syllabus, as well as demonstrations of 'The new Doctrine of Lights and Colours'. Prisms and 'microscopes of the best contrivance' were explained and demonstrated as well, and astronomy was taught by means of instruments like telescopes 'of a convenient length, with micrometers'.[419]

Even though Hodgson may have been responsible for demonstrating the astronomical instruments in the first lectures, Hauksbee's further engagement suggests that he must have been able to use and demonstrate instruments belonging to the realm of mathematical and optical instrument-makers. His experimental accounts give even stronger evidence on this, and show that he was well-acquainted with, for example, telescopes and microscopes, as well as prisms. On at least one occasion, regarding studies of the ascent of drops between glass plates, Hauksbee used a large quadrant with a 4-foot radius, seemingly very familiar with that kind of instrument.[420] There are, however, no clear indications that Hauksbee himself made such devices on a commercial basis. He is not known to have done dialling, for example, a speciality of traditional mathematical instrument-makers. In *Public & Private Science*, Morton and Wess write that supplying apparatus for the public lectures was an effective form of advertising. If this is true, it must only have been valid for a limited array of the instruments, according to the sales-advertisements.[421] Concerning the lectures commencing in January 1705, these

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[417] See: *The Daily Courant*, 8 Nov (1707) and *The Post Man*, 22 Nov (1701).
[418] First advertised: *The Daily Courant* 5 Dec (1704).
[419] The fact that the telescopes were supplied with micrometers is illustrating that the traditional distinction between mathematical and optical instruments was in change.
[420] *PME*. For his familiarity with telescopes and prisms, see page 229; microscopes, page 45; and quadrants page 334.
[421] Morton and Wess (1993), 48.

advertisements suggest that the optical and mathematical instruments could have been on loan from other, more established makers, for example John Rowley, since the course syllabus was also available from him, and that the first lectures were then a joint venture. When astronomy was dropped from the programme a year later, Rowley's name also disappeared from the advertisements, as well as any mention of telescopes, something that supports this suggestion. That the cost of all the instruments needed in the lectures was considerable becomes clear in a letter from Abraham Sharp to John Flamsteed, where Sharp was particularly concerned about the cost of all the instruments that Hodgson had to procure.[422] A possible explanation that I see here is that while the astronomical and optical instruments were on loan from some of the established instrument-makers, the pneumatical and hydrostatical ones belonged to Hauksbee. He had already made and sold these kind of instruments for several years when the public lectures started.

That Hauksbee mastered the use of optical instruments is also clear from a few experimental accounts and his later advertisements on public lecturing.[423] When announcing a new lecture series, starting in January 1712, he made it clear that 'vision was to be explained', together with demonstrations of 'various properties of Optick-Glasses' and 'refraction of light passing through different fluids'.[424] In an advertisement about the same course, three weeks later, he described it as a course in 'Hydrostatical, Pneumatical, and Optical Experiments, &c'.[425] However, if we view Hauksbee the elder's sales announcements, publications and experimental accounts together, optics seems only to have occupied a small part of his activities. There is no evidence of him doing lens grinding, and we know he had to procure some of his glass components from professional glass-men.[426] He performed a few experiments with optical devices himself and showed them in the lectures, but never commercialized them. See Chapter 4.

One of Hauksbee's most important contributions to natural philosophy, in addition to the air-pump, was his experiments on light and electricity. Such marvels were shown and discussed in the public lecture but a study of his sales-advertisements shows that instruments for creating and experimenting with the phenomena never became commercialized. In this period, light and electricity were still effects confined to the hands of Hauksbee and his machines, and maybe a few other operators. The rotating globe machine, for producing light by attrition, must have been a key component in the demonstrations, but it was never made available for sale through the newspapers. The fact that this machine, as we know it from

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[422] Sharp to Flamsteed, 25 Oct. 1704, in Forbes (ed.) *The correspondence of John Flamsteed* (3 vols, London, 2002), iii, 105-6.

[423] *PME*, 229. See also Chapter 4, page 173-5.

[424] *The Daily Courant* 14 Jan (1712). See Morton and Wess (1993), 50, about a possible conflict in the Hauksbee family.

[425] *The Daily Courant*, 11 Feb (1712). At the same time, Hauksbee Junior run a course titled 'Hydrostatical, Pneumatical, Magnetical, and Optical Experiments', together with Humphrey Ditton. See *The Daily Courant*, 10 Jan (1712).

[426] *PME*, 53. 61, 65, 226

Hauksbee's book, lacks all the beautiful ornaments and woodcarvings that we find on the double-barrelled pump, shows that this was an experimental device and not an instrument intended for sale.[427] Compare Figure 24 and Figure 43.

Mechanics, or instruments used for demonstrations of the topic, are not mentioned particularly in Hauksbee the elder's sales or lecture advertisements. However, we know from other sources that he made pedagogical instruments for demonstrating phenomena in mechanics, for example a miniature cart. This becomes clear in a letter from Papin to Hans Sloane, were Papin described a small wagon that Hauksbee had made from brass. Hauksbee's intention had been to use the model to show that great wheels had advantages over small, but Papin thought it was unnecessary, since he had developed a general rule for showing the same by calculations.[428]

Like pneumatics, hydrostatics, optics and electricity, the area of mechanics must have been one that Hauksbee was familiar with as a lecturer and instrument-maker, but the sales advertisements show that only a limited range of all these instruments were intended for the market. Cupping and anatomy utensils were advertised for sale throughout his career; other typical instruments were single and double-barrelled air-pumps, condensing engines and hydrostatical balances. A comparison of his sale and lecture-announcements shows that the instruments portrayed there overlapped mainly at one point: those regarding rarefying and condensing air. Hauksbee never made optical, electrical and mechanical instruments for sale.

So what kind of instrument-maker was he? From a study of all his advertisements, articles and books, it is not evident that he ever applied the title 'instrument-maker' of any kind to himself. In the lecture advertisements he never gave himself any title except for 'Mr Hauksbee', in the later ones this was followed by 'FRS'. In the sales advertisements, which are more relevant here, he most often named himself as an inventor and salesman. After having described his instruments he normally closed with: 'Invented and Sold only by F. Hauksbee'.[429] Later he changed the ending to: 'sold by F. Hauksbee, Author of them', author must in this context denote the originator and manufacturer of instruments, and not the author of texts.[430] Further, there is no evidence suggesting that he was recognised as a scientific instrument-maker by the established mathematical and optical makers at the time. His production of cupping and anatomical instruments seems to have been shared with neither them nor the surgical instrument-makers of the time.[431]

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[427] Many scientific instruments of the period had both practical and aesthetical functions, and were often build like a piece of furniture.

[428] Royal Society, 'Early letters EL/P1/93. Papin to Sloane, Dec 31, 1711.

[429] *The Post Man*, 3 Nov (1701).

[430] Used from March 1705 and onwards, when he first advertised his double-barrelled pump. *The Post Man*, 1 March (1705).

[431] It has not been possible to find any production of surgical instruments among the instrument-

He was however acknowledged by John Harris in 1704 as an 'Ingenious and Industrious Artificer'.[432]

Hauksbee was an active experimenter and lecturer in natural philosophy, but that didn't make him a natural philosopher. When John Desaguliers looked back on his career he compared the early lectures by John Keill in Oxford, who had been his tutor, with those of Hauksbee, and he preferred to be associated with the former. While Keill's lectures had been a course in 'experimental philosophy', Hauksbee had given 'courses in experiments'.[433] However, the best hints on Hauksbee's status come from himself, as he in the introduction of his book lamented his 'want of learned education'.[434] His subordinate relationship is also clear in the concluding remarks of an experiment on the attrition of glass, using wool-threads to detect attraction and repulsion: Here he says that:

> Now how far this Experiment may serve to explain the Nature of Electricity, Magnetism or Gravitation of bodies, is beyond my sphere to determine; but with all Humility submit it to those Learned Gentlemen of this Honourable society.[435]

Further, in an experiment on the production of 'air' from exploding gunpowder, Hauksbee emphasised that he would not 'venture to determine' the causes. It was sufficient for his purpose to produce observable fact and to show that these matters had such and such properties.[436] Among modern authors, Westfall has shown that next to Newton, Hauksbee was simply a servant and of course no intellectual colleague.[437] Stephen Pumfrey, who has discussed the status of Hauksbee and other experimenters in the Royal Society in considerable depth, concludes that the fellows there did not treat such experimenters as natural philosophers.[438] They were paid lecturers and experimenters belonging to the middle class who laboured for their present livelihood.[439]

From this follows that Hauksbee can neither be grouped as a mathematical nor optical instrument-maker, nor as a draper (see Chapter 1), and not as a natural philosopher either. He *is* difficult to categorize, and I will argue that the picture is even more complicated than the one Pumfrey presents. Pumfrey, who described the scientific lecturer (like Hauksbee) as one of the more extraordinary and paradoxical products of the time, did not discuss his instrument-making business specifically.[440] Pumfrey did not distinguish between Hauksbee's instruments made

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makers studied in the period 1705-1745.

[432] Harris (1704), Preface.

[433] Desaguliers, (1734), Preface.

[434] *PME,* dedicatory letter.

[435] F. Hauksbee, 'An Account of an Experiment', *PT*, vol. 25 (1706-7), 2335.

[436] *PME,* 109. In spite of this, he cannot resist to give what he thinks is a probable explanation.

[437] Westfall (1998), 634.

[438] Pumfrey (1995), 156.

[439] One exception is the German traveller Uffenbach, who described meeting 'the natural philosopher' Hauksbee' in 1710. See: Z. Uffenbach, *London in 1710. From the Travels of Zacharias Conrad Von Uffenbach* W. Quarrell and Margaret Mare (eds.) (London, 1934), 169.

[440] Pumfrey (1995), 135.

for use in lectures and those made for sale, but underlined his role as a workman when compared to the virtuoso gentlemen of the Royal Society. If we turn to those who came after him, it becomes clear that Hauksbee was only the first in a series of actors who specialised in pneumatic and medical instrument making, some of them with connections to the Royal Society. In the next section, I argue that they can be described as a distinct, small, group working parallel with the traditional instrument-makers in London up to about 1745.

### 5.2.2 Hauksbee's followers

Francis Hauksbee the elder had several apprentices and associates who continued his work, and who, in retrospect, can be described as a small, but distinct group of instrument-makers. I will in the following give four short biographies of Hauksbee's followers, and then discuss their most common features. Further, I suggest naming this group the 'Pneumaticians'.

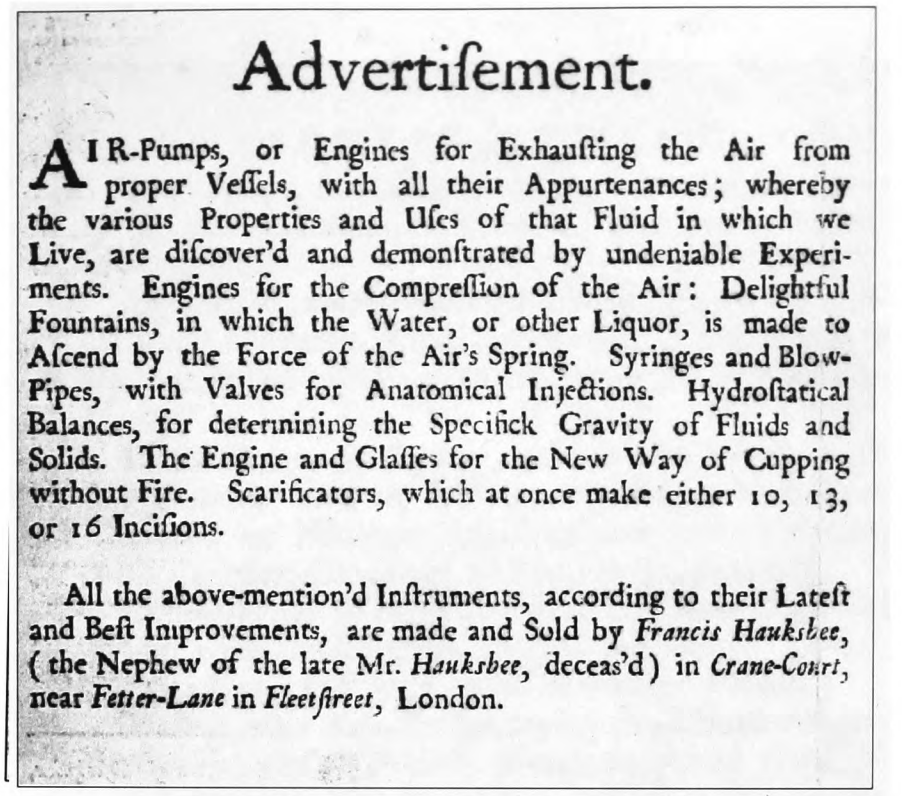
*Francis Hauksbee Junior*

While Hauksbee was still active, he had a prominent follower (and competitor), his nephew Francis Hauksbee Junior. Hauksbee Junior's activities (at least in the beginning of his career) fit into a pattern similar to that of his uncle. The fact that Hauksbee Junior seems to have competed with his uncle and aunt in giving lectures and selling instruments, if only for a short period, only strengthens the impression that he took up a tradition from the elder.[441] Like his uncle he ran a workshop and gave public lectures in natural philosophy, together with philosophers (Ditton and Whiston). Around 1714 he published a book, *A Course of Mechanical, Optical, Hydrostatical, and Pneumatical Experiments*, containing series of illustrations and descriptions of the instruments used in the lectures.[442] The course was scheduled to extend over 26 days, and it contained about 100 different experiments. Later Hauksbee Junior also became engaged in anatomy and chemistry lecturing,[443,444] poetry,[445] as well as developing medicines for venereal diseases (the last of these tasks exposed him to accusations of quackery, however).[446] We also know that he proposed to make reflecting telescopes.[447]

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[441] For a discussion concerning 'the advertisement war' about air-pump valves between Mary Hauksbee and Francis Hauksbee Junior, see Chapter 3, Section '3.1.4.3. Valve equilibrium'.
[442] Hauksbee and Whiston (1714).
[443] *The Daily Courant*, 6 Dec (1720).
[444] F. Hauksbee, P. Shaw, An *Essay for introducing a portable laboratory* (London, 1731).
[445] F. Hauksbee, *The Patch. A heroic-comical poem* (London, 1724)
[446] F. Hauksbee, *A Further account of the effects of Mr Hauksbee's Alternative Medicine.* (London, 1743). See Morton and Wess (1993), 59, for further discussion on this issue.
[447] F. Hauksbee, Proposals for making a large reflecting telescope (London, 1730). See also E. Taylor, *The Mathematical Practitioner of Hanoverian England 1714-1840* (Cambridge, 1966), 128.

The course-book of 1714 was supplied with an advertisement for instruments available from his workshop. It is interesting to observe that while the course contained a whole range of demonstrations within different fields, like mechanics, optics, hydrostatics, electricity and pneumatics – which required instruments from all these areas – Hauksbee Junior's commercial programme was much more limited. See Figure 47).



Advertiſement.

AIR-Pumps, or Engines for Exhauſting the Air from proper Veſſels, with all their Appurtenances; whereby the various Properties and Uſes of that Fluid in which we Live, are diſcover'd and demonſtrated by undeniable Experiments. Engines for the Compreſſion of the Air: Delightful Fountains, in which the Water, or other Liquor, is made to Aſcend by the Force of the Air's Spring. Syringes and Blow-Pipes, with Valves for Anatomical Injections. Hydroſtatical Balances, for determining the Specifick Gravity of Fluids and Solids. The Engine and Glaſſes for the New Way of Cupping without Fire. Scarificators, which at once make either 10, 13, or 16 Inciſions.

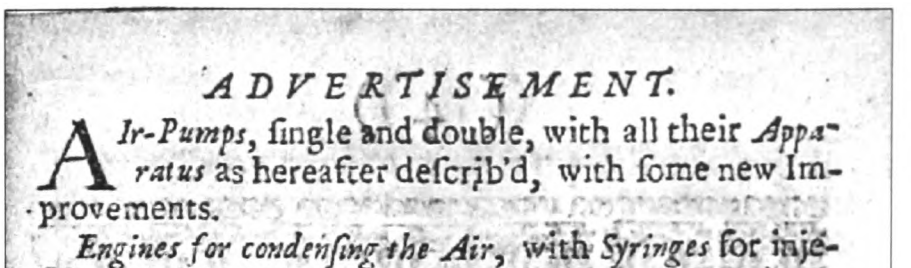
All the above-mention'd Inſtruments, according to their Lateſt and Beſt Improvements, are made and Sold by *Francis Hauksbee*, (the Nephew of the late Mr. *Hauksbee*, deceas'd) in *Crane-Court*, near *Fetter-Lane* in *Fleetſtreet*, London.

**Figure 47.** Hauksbee Junior's advertisement. Hauksbee and Whiston (1714).

The instruments that Hauksbee Junior offered were very much the same as those found in the sales announcements of his uncle. While he could build and use instruments for a whole range of fields within natural philosophy (he gave a greater variety of topics in the lectures than his uncle), the products he offered for sale were mostly in pneumatics, hydrostatics, and anatomy and cupping. The products could thus be divided into two groups: instruments related to experimental philosophy, and instruments related to practical medicine. As a manufacturer of instruments for the public market and lecturer in natural philosophy, the younger Hauksbee followed a similar pattern to that of his uncle.

*Richard Bridger*

The eventual public controversy between Hauksbee's widow Mary and her nephew shows that there were activities going on in Hauksbee the elder's workshop for a period after his death.[448] Richard Bridger, Hauksbee's former apprentice, was in charge of this workshop and was the only person to whom the master had communicated certain secrets about the air-pump valves, according to information in a newspaper announcement.[449] (See Chapter 3, page 126). A joint advertisement from 1717 by Bridger and another practitioner, William Vream, sheds more light on his career, however.[450] This advertisement resembles the original sales advertisements of Hauksbee the elder, as well as that of the younger, but it also contained additional products, for example traditional flame-heated cupping glasses.[451] See Figure 48. As this list demonstrates, the majority of the items were based on the principle of condensing and rarefying air. Many of them were for utilitarian purposes in medicine and anatomy, (cupping, injectors, blow pipes), 'food processing' (Papin's digester), and weaponry (the air-gun). The number of devices that were especially designed for philosophical experiments (air-pumps, condensing-engines, hydrostatical-balances and the mechanical models) represented only one group of Bridger's products.



*ADVERTISEMENT.*

AIr-Pumps, ſingle and double, with all their *Apparatus* as hereafter deſcrib'd, with ſome new Improvements.

*Engines for condenſing the Air*, with *Syringes* for injecting the Air forcibly into any Veſſel; as alſo Syringes for anatomical Injections, with all their Pipes and *Appa-*

Little *Pumps for Cupping*, of Braſs or Silver, with *Scarificators*, that is, Inſtruments for making Ten, Thirteen or Nineteen Inciſions at a time; together with Cupping-Glaſſes of all Figures and Sizes.

*Cupping-glaſſes* to be us'd with the flame of Spirit of Wine, with ſmall Lamps for that purpoſe.

*Blow-Pipes* of all ſorts, with or without *Valves*.

*Hydroſtatical Balances* for trying the different ſpecific Gravities of all Fluids, Metals and Oars, *&c.*

All ſorts of *Weather-glaſſes*, whether *Barometers*, *Thermometers*, *Marine Barometers*, portable *Thermometers*, or *Hygrometers*; that is, Inſtruments for determining the moiſture or dryneſs of the Air at any time.

*Fountains* of Glaſs, or of japan'd Copper, which throw up the Water to a great height in different Figures.

Machines for ſhewing the uſe of all the *Mechanical Powers*; and Models of any Engine for raiſing Water, or any other uſe, to be made upon a ſight or deſcript of the propos'd Engine.

*Wind-guns*, *Papin's Digeſters*; *Apparatus* for performing ſuch Feats, as are pretended to be the Effects of a prodigious Strength, whereby any Man may pull againſt two Horſes, raiſe vaſt Weights, and break a ſtrong Rope.

All theſe are Made and Sold by *Richard Bridger*, (who was Apprentice to the late Mr. *Hawksbee*, *F. R. S.*) at the upper end of *Hind-Court*, *Fleetſtreet*; and *William Vream* Pneumatical Inſtrument-Maker, at his Houſe in *Earl-ſtreet* near the *Seven Dials*, within two Doors of the *Royal Oak*.

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**Figure 48.** Richard Bridger's and William Vream's advertisement. (Vream 1717).

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[448] Taylor (1966), 113.
[449] *The Englishman* 7 Jan (1714).
[450] Vream (1717), advertisement.
[451] Such cupping glasses were presumably cheaper than the syringe type, reaching a larger market.

Even if there was some overlap with other instrument-makers regarding the production of barometers, thermometers and other instruments, I will argue that he very much followed his former master concerning instruments for natural philosophy and medicine. This is not the only correspondence, however. The address given in the advertisement, Hind-Court in Fleet Street, is also the same as the address of Hauksbee's house and workshop from 1712.[452] This makes it clear that Bridger not only took over Hauksbee's production of instruments, but also his workshop. While Francis Hauksbee Junior was engaged in the parallel and competing enterprise of making and selling similar instruments, Richard Bridger was the one that continued the elder's work. Bridger must also have played a role in Desaguliers's lectures, at least until 1714, since these lectures were given at the address of his workshop.[453] We know also that he supplied instruments for a course in natural philosophy in William Watt's Academy in Little Tower Street.[454] The fact that Mary Hauksbee expressed confidence in Bridger in the newspapers, and that he took over her former husband's workshop and stayed at the same address, is better understood when we know that Bridger was married to Ann Hauksbee, Hauksbee the elder's daughter.[455] Based on this, air-pump making in England during the first two decades of the eighteenth century seems (so far) to have been very much a family business. The main actors here were Francis Hauksbee and his wife Mary, Hauksbee's apprentice and son in law Richard Bridger, as well as the nephew, outsider and competitor, Hauksbee Junior.[456]

*William Vream*

Outside the Hauksbee clan, but still close to it, there was at least one more air-pump maker in London during this period: William Vream. He also fits into the pattern described above. Vream had been an employee of Hauksbee the elder and was running an instrument shop in Earl Street, near the Seven Dials, in 1717. See Figure 48. Like Richard Bridger, Vream seems to have followed in the footsteps of his master.

Vream published a pamphlet entitled: *A Description of the Air-Pump, According to the late Mr. Hawksbee's best and last Improvements; with the manner of making Fifty of the most curious Experiments upon it.*[457] The contents of this small publication can be divided into three parts. First, it had a detailed description of Hauksbee's double-barrel air-pump, including a new mechanism, contrived by himself, that replaced the back-and-forth movement of the crank with a circular motion. The benefit of this

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[452] Hauksbee moved from Wine-Office-Court to Hind-Court (both in Fleet street) sometime between Feb. and Nov. 1710. See *The Daily Courant*, 9 Feb (1710) and 6 Nov (1710).
[453] *The Daily Courant*, 5 April (1714).
[454] Taylor (1966), 113.
[455] Clifton (1995), 38.
[456] Even though the Hauksbees range of products was smaller, and they were in business for a shorter period of time, I see some parallels here to the instrument making activity of the Musschenbroeks in Holland. See: de Clercq (1997).
[457] Vream (1717).

modification was an increased pumping speed (which tolerated more leaks) and that the shaking of the pump assembly became eliminated by its rotational movement as opposed to the original back-and-forth momentum.[458] In the next section Vream described fifty experiments with air-pumps and condensing engines, including an illustration of the required air-pump accessories. See Figure 35. This list became a standard description of pneumatic experiments in the first half of the eighteenth century, and is fully reprinted in both the 1737 edition of Harris's *Lexicon Technicum* and Desaguliers's *A Course of Experimental philosophy* from 1743. Benjamin Martin gave a similar catalogue with some additions in his book on air-pumps of 1766.[459] The third element of this pamphlet, consisting of only one page but of crucial importance nonetheless, was the advertisement concerning the philosophical and medical instruments of both Vream and Bridger (Figure 48). Although operating at different addresses, Vream and Bridger made and sold the same kind of instruments and advertised them together, a fact that points to a close relationship between the two.

That Vream had good connections with Richard Bridger and Hauksbee's widow is also suggested by an illustration of Hauksbee's double-barrelled pump that appears in Vream's book. The print by Vream is identical to the one in Hauksbee the elder's own book: it is of exactly the same size, depicting the same details and shadowing, which make it clear that the same copper plate must have been used for both prints. If this particular plate was in Mary Hauksbee's ownership, Vream must have been allowed to borrow it and use it in his own book. The same favour was not granted to Hauksbee Junior. When he published his book, where his uncle's pump was described and depicted, he did not use his aunt's original plate. This is clear because his illustration of the pump is smaller, simpler, and printed as a mirror-image of the original illustration.[460]

William Vream was also engaged in Desaguliers's lectures on natural philosophy. Desaguliers described Vream as his 'operator of Philosophical Machines',[461] and referred to Vream's text on the air-pump in a small book from 1717, *Physico Mechanical Lectures*.[462] Vream's book thus functioned as a necessary supplement to Desaguliers's explanatory texts. In the 1720s, Vream, like Bridger, supplied instruments for courses in natural philosophy in Thomas and William Watts' Academy.[463]

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[458] An illustration of this mechanism given in Desaguliers (1743), plate XXIV, Figure 2.

[459] B. Martin, *The Description and Use of a New, Portable Table Air-pump* (London, 1766), 8-38.

[460] Hauksbee and Whiston, (1714) plate II, Fig. I.
However, if the plate showing the elder's pump was in the property of, for example, the printer or publisher, the use of the plates in the various publications could have been a matter of coincidence, since no 'copyright' existed in the period.

[461] Desaguliers (1744), 377.

[462] Desaguliers (1717), 39. This book could be purchased at Bridger and Vream's workshop, as well as at Desaguliers's house, a fact that shows the strong relationship between instrument-makers and natural philosophers at the time.

[463] Taylor (1966), 145.

With his instruments for use in natural philosophy and medicine, as well as in his lecturing engagements, Vream followed a pattern not unlike that of the Hauksbees and Richard Bridger.

*Stephen Davenport*

This is also true for Stephen Davenport, an instrument-maker who worked in London from about 1720 to 1740. In 1737 he published a book called: *A description of the new invented Table air-pump.*[464] The frontispiece of this book is identical to a trade card by him from 1721, showing a range of pneumatic and hydro-statical instruments, together with several pulleys, intended for demonstrations in mechanics. Cupping glasses of the 'old method' and scarificators can also be seen, together with anatomy-blowpipes. See Figure 49. The structure of his book is similar to that of Vream, with a description of an air-pump, a list of experiments, and an advertisement of instruments for sale. Like Bridger and Vream, the assortment of philosophical apparatus includes air-pumps, condensing-engines and some mechanical models. Davenport also offered digesters and air-guns, and his medical range consisted of cupping utensils and anatomical instruments. In addition, he also supplied tourniquets and embiers for surgeons along with the cupping apparatus.[465]

The most extraordinary thing here is the air-pump, which is of a different type from the single and double-barrelled ones produced by Hauksbee. Davenport's air-pump is depicted in the middle of the image, showing a traditional application, namely to show 'the effects of rarefied air upon the life of animals' as a cat is confined in the receiver. Davenport described his air-pump as 'light and portable, with some improvements'. Both Hauksbee the younger and Vream had built, described and depicted the classic standing air-pump that was contrived by Hauksbee senior. Davenport's pump was of a simpler design, as it was smaller and could be placed on a table. The pressure-indicating gadget was shorter, and presumably less versatile and accurate than Hauksbee's barometer. It also lacked most of the sophisticated ornaments and woodcarvings that were present on Hauksbee's pump.[466]

But Davenport's pump was in many senses important. It was the first novel air-pump to be made in England since Hauksbee launched his double-barrelled model in 1705. Its new simplified design and lower cost shows that there must have been a growing demand for air-pumps at the time, among those who could not afford the

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[464] S. Davenport, *A description of the new invented Table air-pump* (London, 1737).

[465] The word 'embier' is not found neither in J. Simpson (ed.), *Oxford English Dictionary* (http://dictionary.oed.com/entrance.dtl) or in S. Johnson, *A dictionary of the English language* (London, 1755, 73). However, it is most probable the same as 'ambe', an instrument used by surgeons to set disjoined bones. See Croker (1764).

[466] The illustration in Davenport's book shows a few more ornaments than the pump on the trade card. Hauksbee's double-barrelled pump had a cylinder volume of 1240 $cm^3$ (Chapter 3). The corresponding value on Davenport's model can be calculated to 460 $cm^3$, yielding 60% lower pumping capacity.

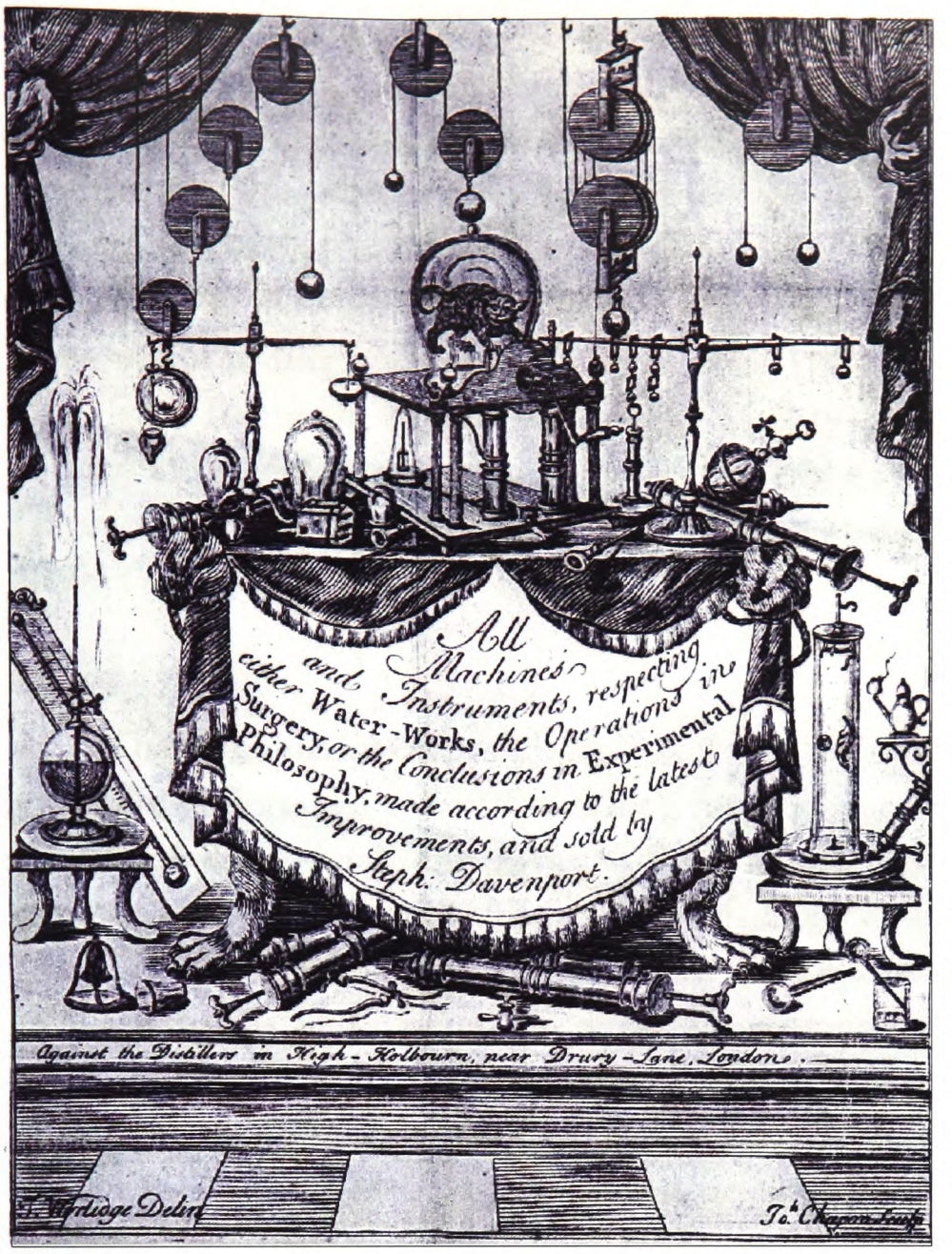



**Figure 49.** Davenport's Card (1721).
The Heal Collection, British Museum.

price of Hauksbee's classic one. A simpler, portable and cheaper model would serve a wider audience, making experiments in Vacuo Boyliano possible for non-professionals too. Also the depicted cat suggests that the products on the trade card were aimed toward amateurs as well, since such experiments must have been regarded more as entertaining demonstrations than experiments of investigation in natural philosophy in this period.[467]

I have not found any direct links between Davenport and Hauksbee or his associates, for example through apprentice- or partnerships, but that he can be described as one of 'them' is evident from Davenport's book.[468] He was well versed in their writings, instruments and experiments. Although he did not mention Hauksbee by name, the description of the table-top pump parallels that of Hauksbee's on a series of points. He also gave an illustration of Hauksbee's capillary experiment. Further, by perusing the text, it becomes clear that Davenport had simply copied Bridger and Vream's list of air-pump experiments.

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[467] A comment on Davenport's trade card is given by M.A Crawforth. He describes it as a 'gruesome reminder of the part that animals had to play in the philosophical experiments at the period. A cat is shown fighting for its breath as the air relentlessly become extracted by the air-pump'. See: M. Crawforth, 'Evidence from Trade Cards for the Scientific Instruments Industry', *Annals of Science*, 42, (1985), 463, 503.

[468] One Stephen Davenport is registered in the Joiners Guild as an apprentice to John Hodgkin in 1715, but according to Crawforth, it is unclear if this was the instrument-maker. See M. Crawforth, 'Instrument-Makers in the London Guilds', *Annals of Science*, 44, (1987), 354.

The most striking similarity between Hauksbee Junior, Bridger, Vream and Davenport is their resemblance to Hauksbee the elder, but they did not just copy and sell his apparatus in an unchanging and derivative way. Their extended product range, together with Vream's improvement of the classic air-pump and Davenport's novel table version, demonstrates that these men were active and innovative, supporting a market with an increasing demand for such products. That there was a lasting market for air-pumps of Davenport's design, for example, is clear from Benjamin Martin's catalogue of 1757, which listed both Davenport's pumps, and large, standing air-pumps.[469] Martin's book from 1766 describes a Davenport pump as well.[470] I will henceforth describe these men as belonging to a distinct group of instrument-makers.

### 5.2.3 The Pneumaticians

I have undertaken a study searching for evidence of the production and sale of air-pumps and related apparatus in England from 1700 to about 1745. Various catalogues and dictionaries on instrument-makers have been consulted. Sources like trade cards, and even sign-boards of old London shops have been studied to look for signals of air-pumps in either print or illustrations.[471] Altogether I have checked about 110 traditional mathematical and optical instrument-makers who flourished in England during this period. It was, however, not possible to detect anything that suggests that there was a production or sale of air-pumps by those makers. The five described above, the two Hauksbees, Bridger, Vream and Davenport, were the only ones that I could find who were engaged in the trade before 1745, and the survey of these individuals showed a common pattern concerning their activities.

All were engaged in manufacturing and selling air-pumps with the necessary accessories for performing pneumatical experiments. Most of them were engaged in lecturing on different fields like optics, mechanics, pneumatics and hydrostatics. They must have been able to use, and in some cases also manufacture, all the instruments that were required for the lecture-demonstrations. They also advertised distinct groups of instruments in newspapers and books. The instruments advertised for sale, however, did *not* reflect the range of instruments they used in the lectures, or in their experiments. The commercial product range was more limited and was concentrated on two areas: instruments in pneumatics and related topics, for example hydrostatics, and instruments and utensils for medical purposes. A technical study of how these instruments functioned reveals that most of them, in both areas, worked on similar principles. The technology

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[469] Millburn (1986), 27.

[470] B. Martin, *The Description and Use of a New, Portable, Table Air-pump* (London, 1766), 2.

[471] Clifton (1995); Taylor (1966); M.A Crawforth (1985); H. Calvert, *Scientific Trade cards, in the Science Museum*, (London, 1971); A. Heal, *Sign Boards of Old London Shops* (London, 1957).

behind the hydrostatic instruments, for example, was often similar to that used in pneumatics, in that it contained cylinders, pistons, and valves. The main difference here was in fact the medium, liquid versus air. A closer look demonstrates that many instruments in cupping and anatomy functioned along similar lines. Much of the technology was the same, working by the principles of rarefying and condensing air. The cupping syringes and glasses were like small air-pumps and receivers. Air was also rarefied in the ordinary cupping glasses, but through expansion by heating and contraction by cooling, rather than by mechanical displacement. The anatomy injectors worked very much like the condensing engines, with a piston for pushing wax or mercury. When air was injected in anatomical specimens, the tool was identical with the condensing engine. The one-way valve in the anatomy blowpipes was also a key component in Hauksbee's air-pumps. This shows that the most commonly-used technology by these instrument-makers was *pneumatics*, which they applied in both natural-philosophy apparatus and in those for use in medicine.

It has not been possible to relate this group to any of the established instrument-makers working in this period. As I mentioned above, they have been described in retrospect as 'philosophical' instrument-makers, although they never applied this term to themselves.[472] If I should suggest a term characterizing this group, I would propose 'Pneumaticians'. This describes them as a distinct subgroup of philosophical instrument-makers, working independently and outside the traditional group of mathematical and optical makers. This term also covers much of the commercial activities of Hauksbee and his followers. According to Warner, the market in England was too small for specialization in philosophical instruments before 1800.[473] But it has been pointed out by others that some sort of specializing took place already with a few individuals around 1700, for example with John Patric, who made barometers.[474] But the activities of Hauksbee and his followers are much better examples of those specializing within distinct functions and instruments in the first half of the eighteenth century, although they had some products in common with other makers. The category can be said to have come into existence with Hauksbee the elder at the beginning of the century, and to have disappeared around 1745. I found no material suggesting that Hauksbee Junior used air-pumps after 1730, and no information at all on Davenport after 1737 and Vream after 1744.

The demise of this group must be seen in the context of two factors in particular. First, in the public lectures, work had most often been divided between a philosopher and an instrument-maker. The first was responsible for explaining and teaching different topics, while the other gave demonstrations and supplied the necessary instruments. Typical examples are Hodgson and Hauksbee Senior,

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[472] Clifton (1995).
[473] Warner (1990), 85.
[474] Morton and Wess (1993), 46.

Whiston and Hauksbee Junior, and Desaguliers and Vream. This lecturing tradition lasted till about 1745, when a new generation of lecturers took over, one where the lecturer and the demonstrator were often the same person. Examples here are the lecturing activities of Benjamin Martin and James Ferguson.[475] The second aspect was the new way of organizing instrument-making. Among the younger instrument-makers were practitioners who manufactured and sold a variety of instruments on a scale that had not been seen earlier. Mathematical, optical and philosophical instruments, including air-pumps and appurtenances, were now offered by one and the same maker, who in fact would organize his activities like a company. The instrument-makers who worked chiefly in pneumatics and medicine could no longer be found; air-pumps had now become part of a much larger industry of instrument production. The first instrument catalogue that included both air-pumps and for example telescopes by the same maker is found in George Adams's *Micrographia* of 1746. It contains a catalogue that includes philosophical, optical and mathematical instruments.[476] A similar list is found in a catalogue by Benjamin Martin in 1756.[477] Another early company selling air-pumps was Heath & Wing, who in 1751 issued a trade card with a Davenport pump printed on it, calling themselves 'Makers of all sorts of Mathematical and Philosophical Instruments'.[478]

Air-pumps are also listed together with globes, scales, quadrants, sun-dials, and other instruments as products made by 'The mathematical-instrument-makers', in a book about London tradesmen from 1747.[479] According to this book, the manufacturing was organized with a master overseeing the work by several production workers, who themselves did not necessarily understand the function of the instruments they made. In other words, a practice that sounds very removed from that of the 'Pneumaticians.'

One tradition within history of science has been to stick to the 'actors' categories', instead of imposing novel taxonomies upon earlier periods, groups or instruments.[480] However, in this case I feel it is appropriate to describe the Hauksbees, Bridger, Vream and Davenport, as 'Pneumaticians'. As mentioned above, Hauksbee never named himself as any type of instrument-maker, while most modern authors have classified him as a philosophical one. An alternative classification is found in Maurice Daumas's work about instrument-makers in the seventeenth and eighteenth centuries.[481] In his chapter about English workshops, he distinguishes between the 'The Opticians', the 'The Mechanicians', 'Other Workshops', and 'The Large Commercial Workshops'. The two first categories

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[475] Ibid, 52.
[476] G. Adams, *Micrographia Illustrata* (London, 1746), 255-7.
[477] Millburn (1986), 27-57.
[478] Crawforth (1985), 509.
[479] R. Campbell, *The London Tradesman* (London, 1747), 253.
[480] J. Bennett, 'A Viol of Water or a Wedge of Glass', in Gooding (1989), 105.
[481] M. Daumas (1989), 228.

correspond to the more common terms 'optical' and 'mathematical' instrument-makers. The last category describes those, who around the middle of the century, had organized their activities in companies, covering almost all branches of scientific instruments, like Adams and Martin. This category is then compatible with the class of 'optical, mathematical and philosophical' instrument-makers working on a larger scale from about 1750. The remaining category, 'The other Workshops', includes the instrument-makers who in the first half of the century were too specialized to fit into the two first groups. It is in this category that Daumas lists the Hauksbees. The instrument-makers Heath & Wing are also catalogued here. Daumas incorrectly attributes production of reflecting telescopes to the elder, and the invention of the electrical, rotating globe machine to the younger. In spite of his imprecision regarding their merits, Daumas's classification scheme makes sense. I argue for a modification: that 'The 'Pneumaticians' are placed alongside 'The Opticians' and 'The Mechanicians'.

There are several reasons for outlining this new, descriptive category of instrument-makers. First, to simply classify them as 'philosophical instrument-makers' will obscure their most characteristic activities – their strong engagement with air-pumps and pneumatical experiments. The term 'philosophical instruments' is also very imprecise, and is in fact only a collective notation for the large variety of scientific instruments that do not fit into the traditional categories of mathematical and optical instruments. Similar arguments can be applied to Daumas's class of 'Other Workshops'. A study of trade cards from the period demonstrated that the instrument-makers themselves did not use the expressions 'Philosophical', 'Optical' or 'Mathematical' with consistency when they described their professions.[482] Secondly, when Hauksbee started his production of air-pumps on a commercial basis, it was something definitely new in England even though Boyle, Hooke and Papin had built a few prototypes earlier and Grew had defined the device in the class of philosophical instruments. Hauksbee thus began a tradition of instrument making that did not belong to any established group. The fact that apparatus and experiments with electricity and light played an important role in Hauksbee's life does not alter the description of him as a Pneumatician, since many of these activities were based on the use of air-pumps. That such experiments were regarded as pneumatic phenomena in this period is also clear from the course syllabus by Whiston and Hauksbee Junior. There, experiments regarding animal life, water fountains, barometric light, as well as electricity were given under the heading of Pneumatics. Likewise the image of the rotating globe machine, which Hauksbee Junior must have copied from his uncle, was placed under the same heading.[483]

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[482] See: Crawforth (1985).
[483] Hauksbee and Whiston (1714) 3, 19.

Finally, the idea of relating this group to pneumatics and distinguishing it from other groups of instrument-makers was already present within the circle itself. Even though Hauksbee never used the term 'instrument-maker' to describe himself – either in advertisements, articles or in his book – his followers did. When Vream signed his small pamphlet of 1717 he added: 'Pneumatical Instrument-Maker' to his name, as Davenport did, twenty years later. As I have shown above, Vream and Davenport made instruments in hydrostatics, mechanics, medicine and pneumatics, but the last subject was clearly the dominant one for both individuals, and the one they were most commonly associated with. To describe these five instrument-makers as belonging to a distinct group, different from the others, is very close to what they did themselves. To use the term 'Pneumaticians' with this group is therefore like using an 'actor's category'.

## 5.3 Private Pneumatics

This section is about the air-pump in private settings. The most famous expression of an air-pump experiment in a private home is of course Joseph Wright's painting *An Experiment on a bird in the Air Pump* from 1768. (Figure 1). In this picture, the attention is directed to the effects of the device, and not to the air-pump itself. I have earlier explained how the pump became such a care-free and common instrument, first by describing the development and commercialization of Hauksbee's air-pumps, and then how this activity was continued by his followers, the Pneumaticians. Here, by examining Vream's book, I argue that situations like Wright's did not have to wait until the second half of the century, but may have already occurred before 1720. Further, I discuss the costs of the relevant instruments and, by examining a painting by Arthur Devis from 1742, show that the air-pump had become a symbol of status for wealthy families at the time of the Pneumaticians.

### 5.3.1 Instructions and experiments

A survey of the public lecture syllabuses reveals that each of the various actors had his own way to present the subject matter. While the original list by Hauksbee and Hodgson contained a series of short-form descriptions of the experiments, and the Hauksbee-Whiston scheme gave keywords and technical descriptions of the instruments, Vream's was different. By scrutinizing Vream's material, it becomes clear that the experiment-descriptions differed considerably from the others on one point: they were more detailed regarding *how* to perform the experiments. For example, when describing the experiments on the breaking of glass-phials with various pressure combinations (see Chapter 4), he instructed the operator:

> When you have made this experiment, wipe your Leather and your Pump-plate, so that none of the glass remain, for it might spoil another experiment.

If the glass fragments were not removed, they could make small cuts in the leather, which in turn would produce leaks since the leather acted as a gasket between the receiver rim and the pump plate, an occurrence that definitely would spoil the next experiment. Further, Vream instructed the readers to exhaust the receiver after every gunpowder-explosion, since the generated air might burst the receiver; he also advised pre-heating the receiver before it was placed over the glowing iron – if not, it might become cracked by the heat. Finally, when such an experiment was over and air was to be let into the receiver (presumably by the air-inlet screw), it had to be done in steps to prevent cracking (from the in-streaming, colder air).[484] None of the other lecturers gave such detailed instructions. Hauksbee described similar issues in his experimental accounts, but they never found their way to the course syllabuses.[485] To see the difference between the syllabuses, a synopsis of Hauksbee/Hodgson's, Hauksbee/Whiston's and Vream's texts on the gunpowder experiment is given in Table 5.

A thorough reading of Vream's 50 instructions leaves us with the question of why he goes into all these details. The usual, modern understanding of the public lectures has been that a natural philosopher, for example Hodgson, normally gave the lectures, and an instrument-maker, for example Hauksbee, performed the practical demonstrations.[486] But if the experiments were to be shown by an experienced instrument-maker in the Vream/Desaguliers case, why all these details? Why all these painstaking descriptions on how to handle, mount, connect, and place the various components relative to each other, required for making an air-pumps experiment? It could definitely not have been written for the instructor in charge of supplying and demonstrating the instruments in the lectures. Such instructions were too obvious for an experienced operator. Neither would it have been necessary for the lecture audience to read all this, since the text was too detailed and complex for just understanding how the experiments worked.

The impression we are left with is that this is not written solely with the audience of public lectures in mind. The text was of course useful in such a setting, but the target group seems to have been people who wanted to do experiments without being accompanied by a specialist. In other words, the detailed descriptions on how to set up and perform the experiments seem to have been meant as instruction in a 'do-it-yourself' situation. If this was the case, it opens up a whole new dimension of the use of the air-pump in this period. The pump had gone

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[484] See: Chapter 3, Section 3.1.2.2. 'The vent valve'.

[485] See for example Hauksbee's experiment on firing of gunpowder in: F. Hauksbee, 'An Experiment', *PT*, Vol. 24 (London 1705), 1807.

[486] Morton and Wess (1993), 43; Steward (1992), 95.

**Hauksbee and Hodgson, 1705-10.**

Experiments about Firing of Gunpowder, Aurum Fulminans, or any other easie inflammable Matter, on a Candent Iron.

**Hauksbee Junior and Whiston, 1714.**
**25th Day, the firing of Gunpowder.**

Fig. 3. Is a contrivance to make Explosion of gunpowder in Vacuo: where H D is a red hot Iron, standing on its Pedestal E, within a Receiver GC; and F is a cork, made above like a dish, to contain the Gunpowder; which by the pulling up and thrusting down a strong wire, with a hole like the Eye of a needle, is in a certain Quantity let fall every time upon the hot Iron; and on the Explosion produces a Flame, and Factitious air, but very little sound, by the reason of the Absence of the Air that should convey it.

**William Vream, 1717.**

35. When you would fire Gunpowder in vacuo, take a Gallipot, and inverting it, set the Gunpowder Iron (that you have with the Pump) upon the Pot, having first made it red hot; cover it with your Gunpowder Receiver (which must first be warmed by Degrees, lest the Heat from the Iron should crack it) and having exhausted it , by moving the slip wire up and down, you will let fall a small Quantity of Gunpowder upon the hot Iron, were it will fire Corn by Corn; when you let in the Air again, let it be by little and little, lest you crack the Receiver. N.B. After every Explosion exhaust the Receiver, because the Gunpowder generates air, and might burst the Receiver.

**Table 5**. Excerpts from instructions on gunpowder-experiments in the public lectures. The apparatus is depicted in Figure, 35, *Fig 23*; and Figure 40.

from being a troublesome and disputed instrument in the seventeenth century to a well-functioning and commercially available commodity for research and public demonstrations in the first years of the eighteenth, and here we find evidence of it entering the private (non-professional) sphere. An association to Wright's painting is not far away, although there a specialist lecturer operated the pump. Vream's book appears therefore not only to be a supplement to Desaguliers's lectures, though it had served an important function there, but also to instruct private buyers of his air-pumps on how to do experiments at home, with family and friends as onlookers, and without any natural philosopher or instrument-maker to guide and help them. From this it follows that both the air-pump and the necessary equipment had become so refined and reliable that the presence of an instructor was no longer required. The influence of Hauksbee the elder is evident here. Vream made and sold air-pumps of Hauksbee's design and described them in his book, carrying the subtitle: *according to the late Mr Hawksbee's best and last Improvements*. Most of the experiments, now explained for a non-professional public, had already been made and described by Hauksbee, including precautions on how to avoid harm and prevent damage to the equipment.

The character of Vream's book also signals that a market had emerged for this kind of product: it was now possible to sell air-pumps, accessories and instruction-manuals to private individuals for demonstrations at home. This is also supported by the fact that the Pneumaticians continuously advertised such equipment in the newspapers, and that Stephen Davenport launched a smaller and cheaper pump, suitable for private use, a few years later.

### 5.3.2 Prices and customers

What was the cost of the instruments? Who could afford to buy the various products? There is not much information on the prices of Hauksbee and his followers' products. I have only been able to find two examples, one is from January 1701 when Hauksbee announced that former customers could come to his workshop and have their cupping utensils modified 'for 6d pr. Glass and 12d, the Engine'.[487] This does not help much, since these prices were for replacing some minor components only. The cost of materials and production of air-pumps must have been considerably higher. The other example comes from Zacharias von Uffenbach, who bought Hauksbee's book for 6 shillings during a visit to his house in 1710.[488] A survey of advertisements and writings from the other Pneumaticians did not yield any suggestions on prices either.[489] It is first with Benjamin Martin in the 1750s and 1760s that we learn the cost of such instruments. In a book published in 1766, Martin made it clear that Hauksbee's double-barrelled pump was a very expensive instrument.[490] He said that the air-pump received 'at last an elegant and magnificent form from the Ingenious Mr. Hauksbee'. Martin called it the 'standing Air-pumps', and it is clear that such pumps were still in use and available, 'for those who will go for the price of it'. That this was really an expensive instrument is clear from a price-list issued by Martin in 1757. The list contains prices of a series of mathematical, optical and philosophical instruments, including different kinds of air-pumps.

These were prices given fifty years after Hauksbee, and it is debatable whether they can be used to determine the price-level on instruments in the beginning of the century. The problem of translating prices from earlier periods to our own present day is well known. To do the reverse, in this case adjusting 1750 prices to the level of 1700-10 for an idea of the costs of Hauksbee's products might, also be difficult. On the other hand there exist some hints that can help. First, several investigations show that prices in general were relatively stable throughout most of the eighteenth century.[491] One source estimates an increase of about 6% in costs for essential articles from 1710 to 1760, another indicates in fact a small decrease during the

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[487] *The Post Man,* 2 Jan (1701).
[488] Uffenbach (1934), 77.
[489] Hauksbee Junior; Vream; Bridger; Davenport. See *The Pneumaticians.*
[490] Martin (1766), 1-2.
[491] J. Burnett, *History of the cost of living* (1969). Reprint: (Aldershot, Hampshire 1993), 131.

same period, where prices on metals like lead and copper sank even more than household products.[492] By comparing Uffenbach and Martin, it becomes clear that the cost of scientific instruments must have been more or less stable over this period. Uffenbach mentioned the prices of some instruments that he bought during his stay in London in 1710. For example, a perspective-glass by Edmund Culpeper, 'especially for use at the play' cost 6 shillings.[493] Martin, 50 years later, sold opera-glasses from 5s to £1-1s.[494] Barometers, specially made for use on ships, were offered to Uffenbach by John Patrick for 2 guineas and upward.[495] Martin charged 1 pound and 7 shillings for 'the best sort of barometers', and 2-12-6 for a barometer, thermometer and a hydrometer in the same frame.[496] As far as these items are comparable, it suggests that the price level on scientific instruments in Hauksbee's time were not so different from those in Martin's period. Second, the instruments that we would like to compare were all of the same type, and consisted of the same sort of materials, as well as required a similar amount of manufacturing work. It should therefore be possible to use Martin's prices as indications on the actual cost of Hauksbee's pumps and other instruments that he and Martin had in common.

In Martin's catalogue of 1757, a large standing air-pumps cost £13-13s, and a pump of Davenport's design £9-9s.[497] He also gave the price of a single-barrelled pump, £2-12s-6d. All three came with 'apparatus', going for £7-7s, £5-5s, and £1-1s. He produced a great variety of instruments, among them also injectors as well as cupping syringes and glasses, a practice that must have been 'inherited' from the Pneumaticians. The price of an injection syringe was even higher than a single-barrelled air-pumps, £3-3s. A small brass syringe for cupping, with glasses, was sold for £1-1s.

Based on these values, I would estimate a price of about £13 on Hauksbee's double-barrelled pump, and about £9-5s for Davenport's table model. However, to suggest a price of about £2 for a Hauksbee's single-barrelled pump would not be correct. As I showed in Chapter 3, the manufacturing of the classic pump required at least double the amount of brass and woodwork compared to the single-barrel model, which should suggest a price difference of 50%, indicating a price of £5 to £6 (Martin's single-barrelled pump must have been a simple hand-held model). Following the same line, a set of Hauksbee's cupping utensils should then be valued at £1, and an injector syringe at £3. If Hauksbee also supplied simple hand-held, single-barrelled air-pumps, they would go for about £2 following the same estimate.

According to D. J. Bryden, who has discussed scientific instruments advertised publicly in the period up to 1714, there were no announcements from instrument-

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[492] Ibid. 132-3. (The Phelps Brown Index; the Schumpeter-Gilboy Index).
[493] Uffenbach (1934), 145.
[494] Millburn (1986), 35.
[495] Uffenbach (1934), 145.
[496] Millburn (1986), 29, 45.
[497] Ibid, 27.

makers in London that referred directly to the cost of the actual instruments. A plausible explanation that he gives is that the market of such commodities was small and that the trade served professional clients only, implying that the customers knew the price-level beforehand. To give the costs was therefore not necessary, as the role of the advertisements was more to identify the different instrument-makers and their various products.[498] This suggests that the market for Hauksbee's air-pumps was relatively small, and that the sales advertisements were a combination of a means to promote himself and his latest achievements, as well as informing new customers of a new way of cupping. Both issues would increase his public status. The costs given about the available modification of his cupping syringes can be explained by the fact that the users of his cupping utensils likely formed a different and larger group than the users of philosophical instruments, and that he had customers outside London.

### 5.3.3 Status and pumps at home

The price level of Hauksbee's philosophical instruments clearly excluded large groups of the public. For a craftsman working in London in Hauksbee's period, the cost of an air-pump with apparatus corresponded to half a year's income. For people who could afford to buy it, it did not only serve as a means for rational entertainment at home, but also as a symbol of status. This is clear from a painting by Arthur Devis from 1742-3, titled *John Bacon and his family.* See Figure 50. This picture is described as a 'conversation piece': small, informal paintings of people in a landscape or a domestic scene, presenting themselves as they were seen in daily life or *wished* to be seen.[499] John Bacon, his wife, and four children are depicted in the foreground of a large room, but what also stands out are the several scientific instruments along the right wall and in the background. A reflecting telescope sits on a shelf by the window, and next to it is a large, transit quadrant on a tripod. Two twinned celestial and terrestrial globes can be seen on the floor in the adjacent room, on the table lays a compass microscope in its box, and behind it is an air-pump. The portrait above the bookcase to the left is said to be Edmund Halley, who was a Professor in Geometry in Hart Hall at Oxford when John Bacon matriculated in 1727. The medallion portraits on the wall showing Milton, Pope, Francis Bacon and Newton further display Bacon's intellectual interests.[500]

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[498] D. Bryden, 'Evidence from Advertising for Mathematical Instrument Making in London, 1556-1714', *Annals of Science,* 49 (1992), 335. The only exception was some paper-instruments made by Joseph Moxon.

[499] E. D'Oench, *The conversation Piece: Arthur Devis & His Contemporaries* (New Haven, 1980), 1-3.

[500] Ibid, 45-6. See also: The Harris Museum and Art gallery, *Polite Society by Arthur Devis.* Exhibition catalogue. (Preston, 1983), 9-10; 22; 43-4.

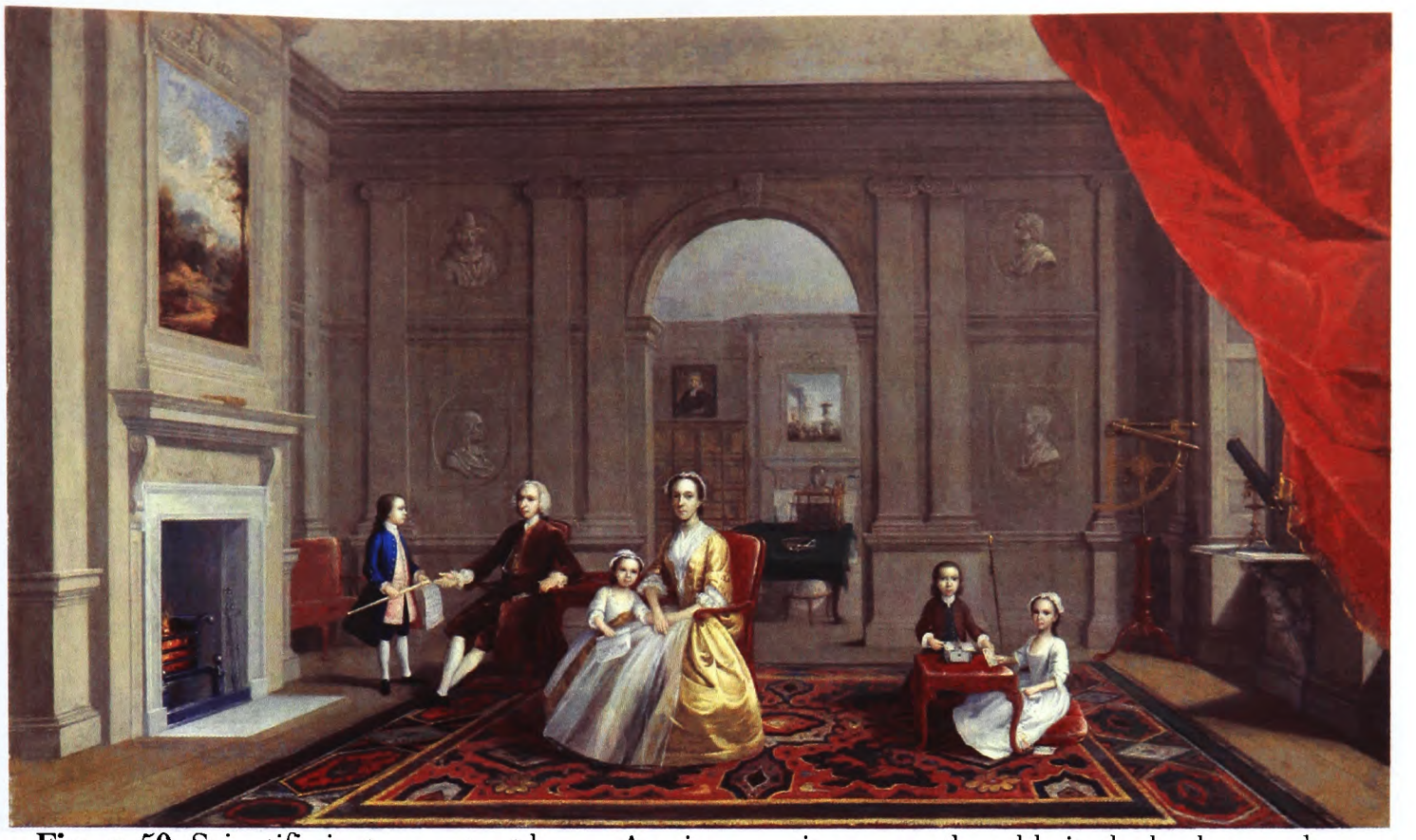


**Figure 50.** Scientific instruments at home. An air-pump is seen on the table in the background. A. Devis, *John Bacon and his family* (1742). Yale Center for British Art (New Haven, Conn.)

This is a family portrait in an idealised setting. It is unclear if the interior existed at all, most probably it was a contrived and artificial space set up to underline John Bacon's aspirations of being a learned gentleman. Being surrounded by scientific instruments in his family portrait would definitely highlight this. My point here is that an air-pump was used for such a purpose. So far, neither models nor makers of the instruments have been identified; I will argue that pump is of a Davenport type. This becomes clear by comparing Davenport's pump in Figure 49 to the one in the painting. Both are standing on a table and have two barrels driven by a crank, and both have four characteristic corner-columns, separating the lower and upper pump-plates. See Figure 51. In the painting, all of the three classical instrument-categories are represented. Exemplars of mathematical, optical and philosophical instruments are shown, the air-pump having the honour of representing the last group. This signals the general status that the air-pump had reached at this stage, and it is interesting to observe that it was not Hauksbee's elegant, standing model that was used, but a cheaper and simpler one, originally depicted with a cat in the receiver and coming with a 'do-it-yourself' manual.

According to the genre of this type of art, the painting itself is no direct guarantee that John Bacon performed experiments in pneumatics at home. But I find it likely that he did, since his friends portrayed him as a 'gentleman of distinguished Merit and Learning', and 'well versed in Philosophy and Natural Knowledge'. He was also described as 'desirous of offering himself as a candidate

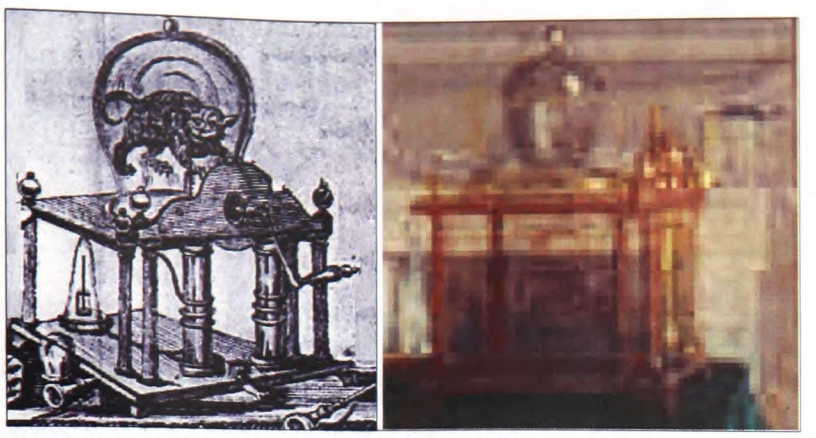


**Figure 51.** Davenport and Devis's air-pumps.

for election into the Royal Society', a wish that was fulfilled in 1750.[501] The air-pump in the painting, whether used in practice by Bacon or not, served therefore as a status-enhancing device and as an element in his 'long running application' for membership to that noble organization.

### 5.3.4 Reaching Wright

When, and how, were the circumstances in Wright's painting reached? The painting, *An Experiment on a bird in the Air Pump* (Figure 1) is called 'one of British Art History's canonical images' (M. Craske)[502] and 'one of the wholly original masterpieces of British art' (E. Waterhouse).[503] Measuring 183 x 244 cm and hanging in the National Gallery in London, it is a well-known and a much-discussed piece of eighteenth-century art. There exist series of commentaries and books on the painting and the painter, and more studies are in progress. The scene in the image is rather dramatic: a dying bird confined in a glass vessel. Most commentators have thus focused on the emotions among the onlookers, such as contemplation, excitement, anxiety and indifference, as well as the overall situation that is created by an experiment in a private home. The outer context of the painting has traditionally been described as a form of intellectual culture in the provinces. However, among all the commentaries that I have been able to study, no one has focused particularly on technical aspects of the air-pump. It is also clear that one of Wright's intentions was to display the *effects* of the pump, and not, for example, how it worked.[504]

As I showed in the Introduction, such issues were particular important in Boyle's meticulous and detailed sketch of his first air-pump about 100 years earlier (Figure 2). Boyle's pumps were controversial and troublesome devices, and the components in the picture can be seen as rhetorical elements in his attempts to convince the readers about the soundness of his results. I argue that such technical matters are *not* part of Wright's message. The pump is depicted as an instrument that has done its job – evacuated the receiver – and no further attention is given to it. It is not operated at the moment; no hand is driving the crank, which indicates a

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[501] The Royal Society, GB 117, Ref no EC/1750/14, John Bacon.
[502] Ref: Dr. M. Craske, Oxford Brookes University
[503] J. Egerton, *Wright of Derby* (London, 1990), 58.
[504] See the Introduction, page 19.

leak-tight and trouble-free construction.[505] Focus is on what it can do, not on how it works, and this fits perfectly with the various definitions of black-boxing, for example by John Lienhard, who describes it as metaphor for 'our retreat from understanding how things work' (no one in the painting seems interested in how the pump works).[506] How did the pump arrive at this stage? This was one of my goals with the present study. Now I have reached it, first by showing how Hauksbee developed his reliable double-barrelled air-pump from cupping utensils, then by discussing further maturing of the vacuum concept, and in this chapter by examining aspects of public and private pneumatics.

The fact is that the possibility of making air-pump experiments at home was reached as early as the 1720s. By 1740, situations like in Wright's painting (where a philosopher performed the experiment) were already exceeded, and this is exemplified by John Bacon's family portrait.

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[505] The pump depicted in Wright's painting has never been identified properly. Most commentators describe it as similar to one used by Ferguson, (Egerton, 58; B. Nicolson, *Joseph Wright of Derby* (London, 1968), 113), others point to Martin's air-pump tradition (Craske). However, I argue that the pump in the picture is an artistic construction, composed of elements from the two most important English air-pumps, Boyle's first version and Hauksbee's double barrelled model. The receiver in Wright's painting is definitely Boyle's, mounted above the structure and with the access-cover on top of it. This likeness becomes even clearer in Wright's first study of the painting (Nicolson, plate 59), where more details of Boyle's pump are sketched, for example the stopcock below the receiver, and the suspension-stud on the top-lid (*S* and *8* in Figure 2). The pumping section, which is the frame with the two barrels and the crank, situated below and to the left of the receiver, is clearly of Hauksbee' design (Ferguson used a Hauksbee-pump, see J. Ferguson, *Lectures on selected Subjects* (London, 1776), plate XIV). Wright's draft also contains instruments that not are shown in the painting, for example a lung-glass, like the one in Figure 38. The large bowl is shown filled with a liquid, but contains no 'skull'. The components that constituted the air-pump in Wright's draft and painting, as well as the pneumatic instruments shown there, were thus all made before 1710 (The Magdeburg Hemispheres, 1656; Boyle's pump 1659; Hauksbee's double-barrelled pump, 1705; and the lung glass 1706). A further discussion of this topic, especially why Wright choose to depict the old receiver of Boyle, and not Hauksbee's, which he must have seen demonstrated by Ferguson, would be an interesting task. However, this undertaking, together with a possible reinterpretation of the painting based on these facts falls outside the scope of this thesis.

[506] J. Lienhard, *The Engines of Our Ingenuity* (Oxford, 2000), 170.

## Conclusion

I have in this chapter given examples of how air-pumps and cupping utensils were used in the public lectures to explain weight, pressure and spring of the air, as well as the phenomenon of 'air in the flesh'. Similar issues, for example experiments on animals concerning bonds between air and life were also discussed in the previous chapter.

Then I demonstrated how Hauksbee and his followers formed a small but distinct group of instrument-makers that worked particularly on two areas: pneumatics and related issues, and cupping and anatomy. Most of them were also engaged in public lecturing where they used a greater variety of instruments than those advertised for sale. I named them the 'Pneumaticians'.

Further, I showed that there must have been a private market for air-pumps and air-pump accessories early in the century, as well as that air-pumps in private settings signalled wealth and status. This became clear by examining the products of two of Hauksbee's associates, Vream's 'instruction manual' from 1717 and a description of Davenports table-pump from 1721; as well as a painting by Arthur Devis from 1742, depicting a Davenport pump. Based on this evidence, I claimed that moments like the one depicted in Wright's painting could have taken place in London already around 1720. No improvement of the air-pump from Boyle and Papin's efforts in the 1670s to Hauksbee's start in 1699 is known, and no import of foreign pumps in the period can be found. Therefore, the transition from Boyle to Wright, regarding both pump-technology and availability must in fact have taken place in a period of about twenty years at the beginning of the century, a development that can be clearly attributed to Francis Hauksbee and his followers. These men managed to transform pneumatics into a recognized field within natural philosophy, to a state with its own accepted methods, terminology, literature, instruments and craftsmen.

Nevertheless, there is one group of air-pump applications undertaken in the same period that can be classified as neither public, nor private pneumatics. These are various uses of the pump where the intention was not teaching or entertaining, but to produce novel matters of fact. I have already pointed to Hauksbee's experiments in electricity and optics (Chapter 4), first performed in his workshop and then demonstrated and discussed by professionals in the Royal Society. So far, little or nothing about other experimenters doing research by air-pumps in this period is known. This is the topic of my final chapter.

# Chapter 6
# Air-pumps and research-practice after Hauksbee

## Introduction

This chapter addresses the air-pump as a research instrument. From a modern perspective, the air-pump of the early eighteenth century is known mostly as an instrument used for demonstrations of facts obtained by Guericke and Boyle in the previous century, and for 'rational entertainment'. Anne. C. van Helden writes that the 'number of scientists doing research with the air-pump never was very large', but describes Hauksbee as a notable exception.[507] However, Helden gives no references, and I have not been able to find any studies that focus particularly on the research and production of new scientific evidence facilitated by air-pumps in this period. Questions of whether the air-pump was used for research at all, or, if that was the case, what kind of research it was, and by whom it was done, seem never to have been properly addressed. This is what I do here. I will look beyond the practice symbolized in Devis's and Wright's paintings and into research-practice, discussing a few examples. My aim is not to give the whole story of research by air-pumps, but to show that such activities definitely took place; a perspective which is required to see the scope of pneumatics in the period. Further it took place when the area was still dominated by the Pneumaticians.

I emphasise three fields, which today would be described as 'basic research', 'applied research', and 'manufacturing'. First, I discuss Stephen Hales's use of the air-pump in studies of plants and animals, as well as in a test of a 'gas-mask' for miners. Second, I look at Alexander Monro's methods for preparing pathological specimens by air-pumps.

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[507] Bud and Warner, (1998), 17.

As in Hauksbee's experimental writings, the air-pump was vital, but not accentuated, which I explain by the state of 'black-boxing' that it had reached. I argue that the few examples of research by air-pumps in the period do not necessarily imply few such applications, but that the obscurity was due to the qualities of the pump, now being a trouble-free device and a socially accepted tool and method, and therefore less noticed and emphasised.

## 6.1. Basic research

Hauksbee is recognized as one of the few who used the air-pump for research and investigations in the period. I have earlier discussed two of his experiments, one on the production of luminous matter in an evacuated glass-globe, and one measuring the refractive indices of a vacuum, pressurized and normal air (See Chapter 4). Here, the vacuum was applied as a physical parameter. In other experiments, he used a vacuum in the more traditional way, as an environment, for example, in studies of propagation of sound through air of various pressures, and on capillarity in a vacuum. A survey of all his approximately 120 experiments shows that about 60% were undertaken by means of air-pumps.

Another early experimenter was William Derham, already discussed in Chapter 1 and 3, who studied the behaviour of pendulum-clocks in a vacuum as well as undertaking various experiments on animals.[508] Further, Stephen Gray used an air-pump in his studies of electrical attractions;[509] yet another example is found with the reverend Stephen Hales.

Stephen Hales (1677-1761) is well known for his experiments on plant and animal physiology. His studies of the hydrostatics of sap in plants and blood in animals are found in *Vegetable Staticks* (1727),[510] and *Haemastaticks* (1733).[511] Both these publications are described as pioneering works. He is said to have 'raised plant physiology to a new level',[512] and that his experiments 'led to the discovery of blood pressure'.[513] However, the fact that Hales used air-pumps in these investigations is not well known, and definitely not part of the modern history of early air-pumps.[514]

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[508] Derham (1714), 8.
[509] S. Gray, 'A letter from Mr Stephen Gray to Dr. Mortimer', *PT*, vol. 37 (London, 1733), 289.
[510] S.Hales, *Vegatable Staticks* (1727). All references are to the reprint (London, 1969).
[511] S. Hales, *Haemastaticks* (London, 1733).
[512] A. Morton, *History of Botanical Science* (London, 1981), 246.
[513] L. Acierno, *The History of Cardiology* (London, 1994), 493.
[514] Hales's use of an air-pump is briefly mentioned in: D. Allan and R. Schofield , *Stephen Hales, Scientist and philanthropist* (London, 1980), 39.

### 6.1.1 Plants

In *Vegetable Staticks,* Hales described a series of experiments on trees and animals that involved an air-pump, but he seldom referred to the pump itself. One example is a study of perspired liquids from various trees where Hales wrote that he could not find any difference in taste from them, that the liquids were very clear, and that all had a specific gravity close to water. Further, he marked that 'nor could I find many air bubbles in them, when placed under the exhausted receiver'.[515] However, the air-pump was not mentioned. The only hint Hales gave of a pump being involved was the expression: 'the exhausted receiver'. This expression likely reflects an extensive use of the pump: for each kind of sap that was tested, the operation had to include removal of the receiver, inserting a vessel with the fluid, replacing the receiver and checking for leaks before pumping could take place. Then pumping while looking for bubbles to emerge, waiting, and finally letting in air to prepare for the next sample. The experiment was repeated with saps from ten different trees, requiring at least that many replicated procedures. It could have taken a whole day, maybe longer, to accomplish, but nothing of this laborious process was referred to in the text.

In an experiment on whether air could pass through the bark of trees, he set up an arrangement with a birch-stick (f), turned upside down and protruding out through the top of an air-pump receiver. See Figure 52. The lower end of the stick was kept in a water-filled cistern (x) inside the receiver, which was sealed off at the top by cement around the stick, (z). The top-end of the stick was covered with cement as well (n), and when he 'drew the air out of the receiver', numerous bubbles issued continuously out of the stick in the water, leading to the conclusion that the air had entered through the bark.[516] When reading this account, it becomes evident that the expression 'the air-pump receiver' is introduced abruptly into the text, and in such a way

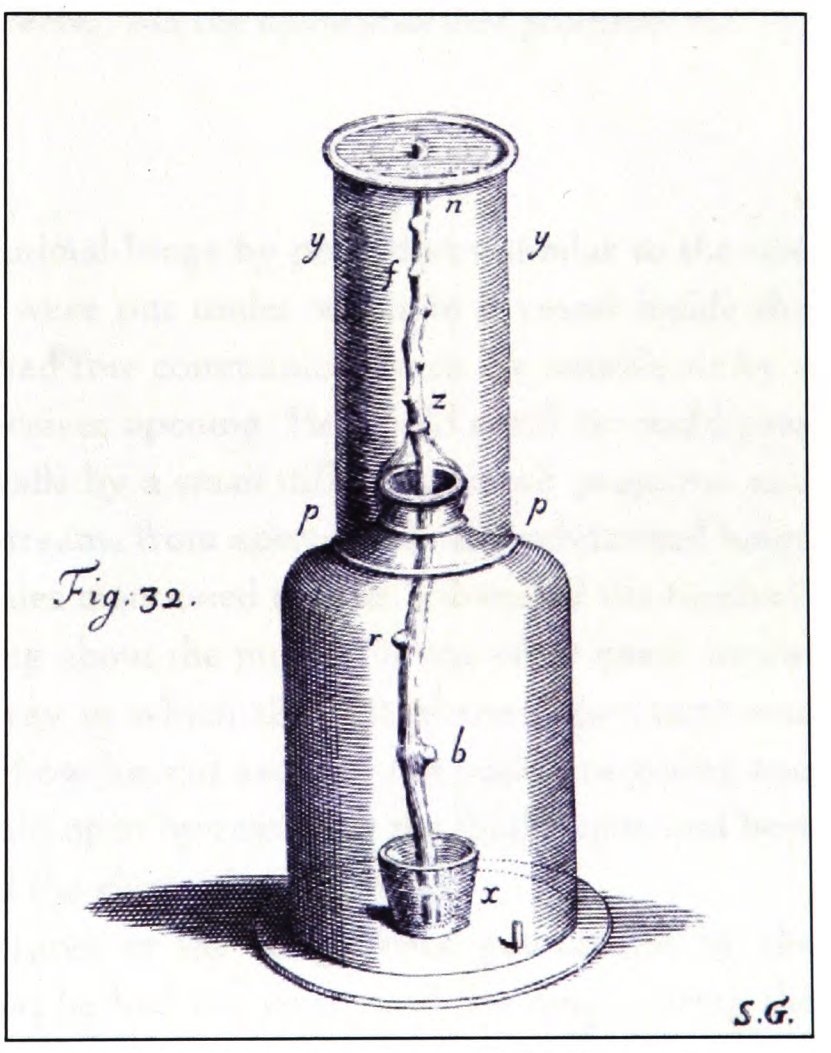



**Figure 52.** Stephen Hales' Air-pumps arrangement. Only the pump-plate and receiver are shown. The cylinder y/y-p/p was not used in the experiments discussed in the text. *Vegetable Staticks* (1728).

[515] Hales (1969), 28
[516] Ibid, 85.




**Figure 53.** Receiver and pump-plate with the connection to the pump-barrels (stud) on Hauksbee's double-barrelled air-pump. Deutsches Museum, Munich. Photo: Terje Brundtland.

that Hales must have expected his readers to be familiar with the device. He did not use words like 'the air-pump', 'pumping', 'leak-tightening', 'pressure reading', etc. Neither is the air-pump itself shown in the illustration; the only hint that it actually depicts an air-pump experiment is the small stud on the pump-plate (close to x), which must be the connection to the pump-barrels. Compare Figure 52 and 53: See also Figure 26. What mattered was the suction that was created in the receiver, not the apparatus that produced it.

### 6.1.2 Animals

Hales also performed studies of animal-lungs by procedures similar to the one above.[517] Like the sticks, the lungs were put under water in a vessel inside the receiver, but the inside of the lungs had free communication to the outside air by a glass-tube protruding through the receiver opening. He would see if air could pass through the substance of the lung-walls by a small difference in air pressure, and reported air bubbles rising in small streams from apertures in the submerged lungs as he drew air out of the receiver. Hales mentioned that he 'exhausted the receiver' to 'raise the mercury', but said nothing about the pump. On the other hand, he did put considerable emphasis on the way in which the rest of the experiment was performed, as he described in detail how he 'cut asunder the bodies of young and small animals', how the thorax was laid open by removing the diaphragm, and how the connection between the lungs and the glass tube was made.

Further, to prove that the apertures in the lungs were not caused by the experiment but existed naturally (that he had not punctured the lungs during the preparation), Hales made another experiment, this time on a live dog. He described how he tied down the dog on its back and cut open a small hole in the thorax near the diaphragm, and inserted a glass tube. The tube was in turn attached to a barometer for monitoring the pressure variations in the thorax. He explained in

[517] Ibid, 142. That Hales saw a similarity between these two experiments is clear since he referred to the same illustration (Figure 52) in both cases.

detail how the experiment was performed, the reactions of the dog,[518] as well as how he 'drew air out of the thorax' through the tube, while monitoring the operation by the height of the mercury. In this example, one must closely examine the text for the air-pump to become 'visible'. It is not mentioned at all, nor that the 'height of the mercury' must have been synonymous with a pressure measurement by the in-built barometer, or that 'raising the mercury' meant a pressure decrease caused by operating the crank. In order for this account to be fully comprehensible, the readers had to know the technical details within these expressions, a prerequisite that Hales must have taken for granted.

Hales's accounts of plant and animal-experiments are excellent examples of successful black-boxing. The pump and the pump-barometer were only mentioned occasionally, in spite of the fact that the air-pump was the most advanced instrument that he used. Clearly, his message was in plant and animal-physiology, not in pneumatics, and a thorough study of the texts is required before the pump becomes noticeable. However, such an attitude squares perfectly with the assertion that 'successful instrumentation is rendered invisible, through transparency and black-boxing'.[519] This explains also why the air-pump has had no place in modern commentaries on Hales.[520] For Hales and his readers, the function of the air-pump was important, not the instrument itself.

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[518] Ibid, 144. The dog died before the experiment was finished. Comments on Hales's attitude to research on live animals is found in N. Rupke, *Vivisection in historical perspective*. (London, 1987), 31.

[519] Gooding (1989), 5.

[520] However, this do not exclude the possibility that Hales had technical concerns about the air-pump himself, but it shows that he didn't see them as part of the experiments.

## 6.2 Applied research

While the air-pump experiments above were undertaken for revealing secrets about Nature, Hales performed others with clear utilitarian purposes. Utilitarian uses of the air-pump, such as attempting to preserve food in vacuum had earlier been undertaken by Huygens and Papin.[521] Hales was concerned with practical improvements in a series of fields, and tried, for example, to develop methods for keeping water sweet and meat fresh during long sea voyages.[522] He also constructed ventilators for improving the quality of air inside ships, prisons and mines,[523] as well as undertaking an air-pump experiment for testing filters for bad air.[524]

### 6.2.1 Filters

In order to simulate a situation of healthy and not-so-healthy air in mines ('subterraneous damps'), Hales used an air-pump to produce a continuous stream of air through a receiver with a burning candle inside it, functioning as a 'sensor'. The aim of the experiment was clearly utilitarian: to find some means to 'qualify and rebate' the deadly vapours that occurred after explosions in mines, and which led to 'certain death'.[525] In a series of experiments and discussions on elastic, non-elastic and noxious (poisonous) air, where Hales used animals, candles and burning brimstone (sulphur) as elements, the pump-receiver functioned as a model of a mine-cavity. He referred again to his illustration (Figure 52), but now the water tank was replaced with a candle, the birch-stick was removed, and three folds of wool-cloth were tied over the mouth of an iron siphon that was inserted through the receiver top. Hales had earlier observed how noxious air could extinguish flames; the purpose of the cloth was to see if such material could be used as a filter for these deadly fumes. He let the air pass through a pot with 'burning brimstones' before it entered the siphon and became sucked into the receiver through the cloth, which caused the candle to go out after 15 seconds.[526] When he repeated this experiment with the cloth removed, the flame was extinguished immediately. Consequently, Hales argued that since the deadly vapours in mines were normally not so strong as these sulphurous ones, miners would preserve life longer when such damps were present, by breathing through many folds of wool-cloth.

This experiment differed from those on plants and animals in two repects. First, the air-pump was used quite differently (something that illustrates the versatility of the instrument). Normally, an air-pump became used for creating a vacuum, but here it was used to produce a constant flow of poisonous air of atmospheric

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[521] See: C. Huygens and D. Papin, 'A continuation of the Experiments', *PT*, vol. 10 (1675), 492-5; Papin (1687), 53-78.
[522] S. Hales, *Philosophical experiments* (London, 1739), 57-94.
[523] S. Hales *A description of ventilators* (London, 1743).
[524] S. Hales, *Vegetable Staticks* (1969). 148, Experiment CXV.
[525] Ibid.
[526] A similar experiment was often demonstrated in the public lectures. See Figure 35 *Fig, 27.*

pressure through a receiver. To check that the receiver-pressure did not sink too much below normal, which in itself would have extinguished the flame, Hales made a test by sucking fresh air through the siphon, the cloth and receiver by operation of the crank. He reported that air passed so freely that the mercury 'did not rise above one inch', and that the candle did not go out until after two minutes. I have earlier shown how the air-pump was used for creating a vacuum in the sense of an environment, and as a physical parameter; here it was simply used as a generator for poisonous air of atmospheric pressure. Second, it had a utilitarian purpose. The contrast between this experiment and the two above illustrates well the difference between those undertaken for producing matters of fact, and those made with a practical objective. The air-pump had a role in both. Moreover, neither in this account did Hales say more about the air-pump than absolutely necessary. He referred to the receiver and the mercury in the same way as before, and must clearly have assumed that the readers were well acquainted with the air-pump – another example of the 'invisible' and black-boxed air-pump.

## 6.3 Manufacturing

This section is about yet another application of the air-pump. Here it was used neither for demonstrations nor for basic or applied research, but simply as a manufacturing device. The issue is the anatomist Alexander Monro's use of the pump for preparation of pathological specimens. Monro (1697-1767) had studied in London, Paris and Leiden and received a lectureship in anatomy at the Surgeons' Company in Edinburgh in 1719, and was admitted to the University there in 1725. He wrote several medical works, some of them with instructions on how to preserve body-parts by different preparation techniques, including the use of blowpipes, syringes and siphons.[527] However, I had to turn to an unpublished manuscript, *A treatise on Anatomical Encheiresis* (1747), to learn that he also used an air-pump for such tasks.[528] Monro is a well-known anatomist, but the fact that he applied an air-pump in his practice has never been discussed before.

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[527] A. Monro Secundus, *The works of Alexander Monro*, (Edinburgh, 1781), 1-10.

[528] A. Monro, *A Treatise on The Anatomical Encheiresis Or manual Part of Anatomy*. (1747). University of Otago Medical Library, ms 169, (handwritten), unpublished. Transcribed by P. A. G. Monro. (1997). C. Lawrence has commented on this manuscript, and discussed Monro's teaching practice in particular. See: C. Lawrence, 'Alexander Monro Primus and the Edinburgh manner of anatomy', *Bulletin of the History of Medicine* vol. 62, no 2 (1988), 193-214.

### 6.3.1 Pathological specimens

The *Encheiresis* is very much a handbook on the art of making pathological specimens, reflecting practice and experiences achieved over many years, at least from around 1720.[529] It contains detailed instruction on the various techniques and uses of hand-tools, as well as giving a list of more advanced instruments for the anatomist, like several sorts of microscopes, a hydrostatical balance, a barometer, a thermometer, a condensing engine, as well as an air-pump with accessories.[530] The classic method for preparing pathological specimens was to inject air, wax or mercury into the body parts to keep their form and to prevent deterioration (see Chapter 1). This text gives detailed instructions on how to use syringes and blowpipes, and practical tasks like cutting, sawing, chiselling, perforating, binding and sewing of the body parts. The air-pump was used as part of an advanced injection system where metal with a low melting point was filled into a specimen suspended in vacuum,[531] a method that he attributed to Wilhelm Homberg (1652-1715) from 1699.[532] The specimen to be filled was placed in the receiver and connected to a tube that was joined by a stopcock to an outside funnel. See Figure 54. (This illustration was found among The Monro papers in Otago, and has never been published). By operating the pump, air would rush into the vessel through the funnel and distend it, and it would be kept like this until all moisture had disappeared from the surface. The stopcock was then closed and the funnel filled with hot melted metal before it was opened again, allowing the metal to run down and fill the vessel 'with all its branches'. According to Homberg, air inside the specimens could create air-pockets and prevent a perfect

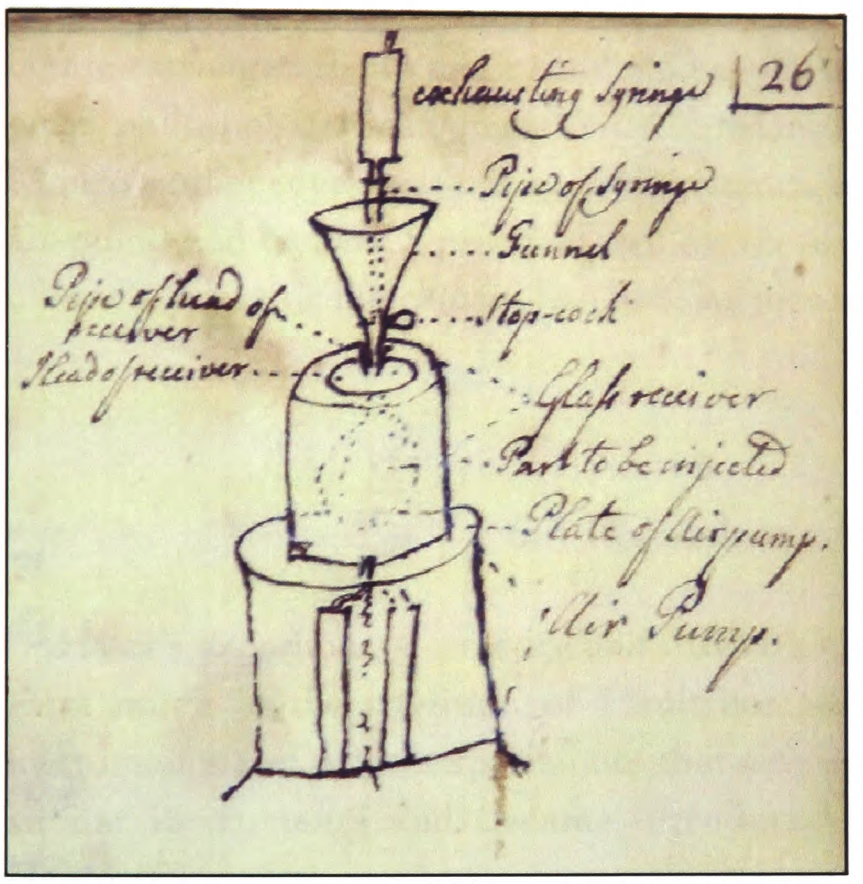



**Figure 54.** Alexander Monro's air-pump arrangement for preparation of pathological specimens. (1740). University of Otago Medical Library, ms 169, unpublished.

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[529] A. Monro, Primus, *The Professor's Daughter. An Essay on Female Conduct* (Edinburgh, 1996), ix-x.

[530] The condensing engine (Hauksbee made and sold such apparatus from 1705) was, for example, used to force water out of arteries and veins after flushing, before they became injected with wax See: A. Monro Secundus, (1781), 7.

[531] For example bismuth.

[532] Monro (1747) 25. See also F. J. Cole, 'The history of anatomical injections', in C. Singer, Ed. *Studies in the History and Method of Science* (2 vols, Oxford 1921), i, 286-343.

filling. To solve this problem, Monro devised a long tube that would fit exactly to the opening of the stopcock in the funnel, with the other end connected to an exhausting syringe. When the specimen had become inflated by the vacuum and in turn emptied of air by the syringe, the funnel was filled with hot metal, the tube redrawn, and the liquid metal would became forced into the vessel by the external air.

What is also striking here is Monro's attitude to the pump, describing it simply as a production apparatus. This is a very different way of using the pump from the one found with Hauksbee and Hales. Much of Monro's activities can of course be categorized as research, for example his overall study of human and animal anatomy. But his use of the air-pump above cannot be described as such; there the pump was simply a tool and applied by the anatomist in the function of being a craftsman. In this application, the pump took the role of a manufacturing tool, with vacuum acting as a production method.

Strictly speaking, it is not possible to talk of the air-pump as a scientific or philosophical instrument in this application. The air-pump as an instrument that creates strange effects and raises philosophical questions is not found here. The term 'philosophical instruments' is still meaningful with Hales's and also some of Monro's other investigations and demonstrations with the pump but not here. The air-pump had become a practical tool for the anatomist, what we see is an example of how a scientific instrument had become turned into a manufacturing device.

## 6.4 Hauksbee's legacy

Hales's experimental practice and Monro's fabrication of pathological specimens were much in the tradition of Hauksbee and the Pneumaticians. Hales used instruments and made experiments that originated from Hauksbee; Monro used similar instruments and became introduced to pneumatics by Hauksbee the younger.

Hauksbee's influence on Hales can be traced back to his student-days. Hales had studied in Cambridge from 1696 to 1708, and must have become familiar with pneumatics and hydrostatics through lectures given there by Roger Cotes and William Whiston.[533] We obtain a good sense of what Hales had been taught by surveying their printed works. From Cotes's textbook, *Hydrostatical and Pneumatical Lectures*, it is apparent that Hauksbee must have been presented to the Cambridge students in an informative and positive way.[534] His experiments and instruments are referred to regularly, and Hales must have been one of those students who saw Hauksbee's double-barrelled air-pump disassembled and reassembled for didactic

[533] Allan and Schofield (1980), 14.
[534] Cotes (1747).

purposes.[535] (See Chapter 3). Cotes and Hauksbee had also met each other, and Cotes had witnessed the 'diligence and care' with which Hauksbee performed his demonstrations; something Cotes could communicate to his students.[536] Moreover, the syllabus of Whiston and Hauksbee Junior's public lectures describes many instruments and experiments that originally were made by Hauksbee Senior. This course-structure bears a strong resemblance to the one in Cotes's book, suggesting that Whiston could have used a similar scheme while teaching in Cambridge, and therefore promoting Hauksbee to his students, including Hales.[537]

If we turn to Hales's own writings, we find an even stronger confirmation of Hauksbee's legacy in this area of natural philosophy. Even though Hales only mentioned Hauksbee by name three times in *Vegetable Staticks,* once by referring to measurements of the weight-relationship between water and air, and twice to his gunpowder experiments, his influence can be seen in both the use of instruments as well as in several experiments.[538]

### 6.4.1 Hales' instruments

What kind of air-pump did Hales use? The supplied figure (Figure 52) leaves no clues on type or maker, and only the small stud indicates that it depicts the base-plate of an air-pump. In this period, three models were available in England, the single and double-barrelled ones by Hauksbee, and the table-model by Davenport – all having an in-built barometer.[539] On one occasion, Hales described how he watched 'the mercury raising nine inches' while he operated the pump. This must indicate an air-pump with a full-length barometer (29 inches),[540] something that excludes Davenport's model, which had a shorter gauge.[541] Consequently, Hales used a Hauksbee-pump, probably a doubled-barrelled one, since he was familiar with this version from Cambridge. Further, he used several other instruments that were included in Hauksbee's product range. One example is a condensing engine with a cylindrical glass receiver, which he used in studies of elasticity of air obtained from tartar.[542] Another instrument he often referred to but without specifying type or maker was a balance. It must have been used regularly, as he

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[535] Ibid, 164. Cotes description of the air-pumps of the 'late Mr Hauksbee must have been written between Hauksbee's death in 1713 and Cotes death in 1716. According to Allan and Schofield, it is of little concern for our understanding of Hales's professional background that most of the available information appears in books written after he had left Cambridge. See: Allan and Schofield (1980), 14.

[536] Ibid,189. Hauksbee demonstrated this experiment on 15 May 1706, in the Royal Society.

[537] Cotes's classification scheme of the various experiments is close to that used in the public lectures by Hauksbee Junior and Whiston.

[538] Hales (1969), 96 (weight of air vs. weight of water), 107 and 129 (Gunpowder). Hauksbee's corresponding accounts are given in *PME* (1719), 94, 104.

[539] See Chapter 5.

[540] Hales (1969), 143.

[541] The cylinder length on Davenports pump is given as 8 inches and the barometer must have been shorter than this. See Figure 49.

[542] Hales (1969), 106.

often gave the weight of small quantities of various sorts of airs and fluids obtained in the experiments. I think the most likely candidate is Hauksbee's hydrostatical balance. This is supported by the fact that Cotes, Hales's teacher, had used and recommended such a balance in his lectures,[543] that Hales referred to Hauksbee's use of the hydrostatical balance to support his own measurements,[544] and that Hales's descriptions of practice with this instrument agrees well with information given by Hauksbee. This balance was introduced in 1706 and was later available from the Pneumaticians. A study of Hales's text shows therefore that part of his experimental activity, both the creation of phenomena (using air-pumps and condensing-engines) and the diagnosis of them (reading the air-pump barometer and weighing) originated from Hauksbee.

### 6.4.2 Hales' experiments

Hauksbee's legacy can be found with some of Hales experiments as well. For example, Hales's efforts in making filters for bad air can be traced back to an experiment originally made by Hauksbee. In October 1710, Hauksbee published an article on how he let air become sucked into an air-pump receiver through pieces of red-hot metal, burning coal, and other such materials.[545] Afterwards he tested its 'quality' by checking how long birds could live and candles could burn in it, and asked if this air was similar to subterraneous fumes. What Hales did here is obvious. Hauksbee had undertaken this experiment to investigate properties of factitious air, concluding that it would kill birds and extinguish flames; Hales used the same arrangement to find a remedy for these deadly fumes. Here, Hales had turned fundamental (basic) research into applied research.

Further, in the course of his extensive work on plant physiology, Hales described an experiment for studying the 'imbibing power of wood-ashes', consisting of a glass-tube filled with dried and sifted ashes where he observed how water became sucked upwards in the tube.[546] Newton had earlier discussed a similar experiment.[547] However, a close reading of Hauksbee's works shows that this experiment, which spanned both pneumatics and hydrostatics, had originally been performed by him.[548] Hauksbee's tests had been part of a series of studies on general capillarity, and he had interpreted the results within the context of the nature of matter and attraction between particles. Hales, however, was more

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[543] Cotes gave a long quotation from Hauksbee's account on the experiments with this instrument. See: Cotes (1747), 190.

[544] Hales (1969), 96.

[545] F. Hauksbee, 'Experiments concerning the Effects of Air Pass'd through Red Hot Mettals', *PT*, vol. 27, (1710), 199-203; *PME*, 282.

[546] Hales (1969), 55.

[547] I. Newton, *Opticks* (London, 1734). Query 31, 391. This experiment was described for the first time in the 1718 edition.

[548] F. Hauksbee, 'Several Experiments Touching the Seeming Spontaneous Ascent of Water', *PT* vol. 26, (1709), 262; *PME*, 184.

practically oriented and used his findings in a discussion on imbibition, capillary transport, and perspirations of moisture in plants. Hales did not mention Hauksbee explicitly, but the parallels between the two set-ups leaves no doubt about where he got the idea.[549]

### 6.4.3 Monro's application

Monro never mentioned the Pneumaticians specifically in his writings. The techniques of preparation of pathological specimens by injection of various substances, as well as to perform this in vacuum, did not stem from this group, but had originated on the continent in the previous century. However, the only known group in Britain that supplied instruments for such undertakings in the period were the Pneumaticians, and a study of Monro's works having air-pumps and pneumatic apparatus in mind, gives several indications of their presence.

Like Hales, Monro's first acquaintance with pneumatics took place in his student-days. His son, Alexander Monro Secundus wrote that he followed the lectures in natural philosophy given by Hauksbee Junior and Whiston, a course where air-pumps, condensing engines and cupping syringes had a prominent place (see Chapter 5). Further, he attended anatomical lectures given by Mr. Cheselden in 1717-1718[550] where Hauksbee Junior was also engaged.[551] The production and sale of anatomical instruments were one of the characteristics of the Pneumaticians, and Monro must have become familiar with such instruments, if not earlier, during these demonstrations.

Moreover, there are elements in Monro's experiments and teachings that resemble some found in the public lectures by Hauksbee and the Pneumaticians. For example, of seven demonstrations by Monro on the functions of the lungs, there was one showing an animal breathing air obtained through a red-hot barrel, and one with an animal confined in a receiver 'till it died' while observing changes in temperatures and pressure.[552] Similar experiments are found in Whiston and Hauksbee Junior's course-plan from 1714, the first one was originally undertaken by Hauksbee the elder.[553]

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[549] The main part of the original instrumentation was the same (the ash-filled glass-tube), the phenomena similar (capillary effects); but the purpose and context of the experiments were different. What we see here is an example of what I will call a 'purpose-shift' of an experiment. Instruments and experimental set-ups that were made for testing specific hypothesis by one experimenter become used for other purposes by later practitioners. Another example of this is Hauksbee's rotating globe (see Chapter 4), which was originally made for studies of light-production in vacuum by rubbing, but became used for explaining the Aurora Borealis by natural philosophers in the second half of the eighteenth century. A discussion of such developments falls, however, outside the scope of this thesis.

[550] Monro, Secundus (1781), x.

[551] Morton and Wess (1993), 56.

[552] A. Monro (1747), 110-1.

[553] Hauksbee and Whiston (1714). Day 25: 'Effects of contented air upon life of animals', and

Monro resided in Edinburgh, but it has not been possible to link the specialised instruments like the injection syringes, the condensing engine or the air-pump to any Scottish instrument-makers. Monro had associations with the instrument-maker James Short (1710-1768), but he is not known to have made air-pumps or other philosophical instruments.[554] According to D.J. Bryden, the Scottish natural philosophy professors in the period turned to London for much of their teaching apparatus.[555] Monro supposedly did the same, and the only known suppliers there of the actual instruments were the Pneumaticians.

Monro gave the background of his air-pump application, but said nothing about the instrument itself. It is difficult to identify the type from the sketch (Figure 54), but I suggest that it was a double-barrelled type in the Hauksbee-tradition. He could possibly have procured an air-pump in Leiden or Paris during his 'Grand Tour', but I find it doubtful since no evidence of import of foreign air-pumps to Britain is found in this period.[556] The two possible models are Hauksbee's free-standing double-barrelled pump, and Davenport's table-version. The sketch shows a circular or oval base-plate with two barrels below it. It is not very accurate compared to the cuts in *PME* or those by Davenport, but since the last one had a square base plate, it points to Hauksbee's model. That Monro used such a pump is also suggested by the fact that one of the surviving Hauksbee-pumps (Figure 24) is found in Edinburgh and originates from about 1720.[557] It is now a part of the Playfair collection. Studies of this pump have identified it as William Vream's version, which was available from 1717. There have been some unsuccessful attempts to associate it with either William Cullen (1710-1790) or Joseph Black (1728-1799).[558] I will however suggest Alexander Monro as a user. A possible scenario is that Monro had learnt about air-pumps generally in Hauksbee Junior and Whiston's lectures, and learnt the preparation techniques for using a vacuum during his visit to Leiden and Paris in 1718-19, and procured the pump in London in the early 1720s. Also the improvement of using an exhausting syringe for evacuating the specimens points to the Pneumaticians, since this could perfectly have been done with a cupping syringe with an automatic valve (there is no sign of stopcock in the illustration).

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'Effects of burnt air upon life of animals'.

554 T.N. Clarke, *Brass & Glass* (Edinburgh, 1989), 1.

555 D.J. Bryden, *Scottish Scientific Instrument-Makers 1600-1900* (Edinburgh, 1972), 11.

556 de Clercq (1997), 151.

557 R.G.W. Anderson, *The Playfair Collection*, (Edinburgh, 1979), 67.

558 Ibid, 69.

## 6.5 The obscure instrument

Why have professional uses of the air-pump got so little attention? Before now, the overall opinions among instrument-historians have been that there was almost no research with the device in England in the first half of the eighteenth century. However, I have given evidence that such undertakings definitely took place. Here I will explain why it is absent from the standard air-pumps accounts.

First, the fact that the pump is more or less hidden in the experimental accounts of the time does not mean that it was not used. The study of Hales's experiments shows that he only mentioned it casually, despite being an important element in his research-practice, and the most complicated instrument applied. The slight emphasis on the device was clearly a result of successful black-boxing. The pump was easy to operate and must have been familiar to the readers, and therefore not worth mentioning. Hauksbee is described as one of the few doing research with the pump in this period, but a closer look shows that he did not take 'much notice of it' in his accounts either (Chapter 4). The air-pump had become 'invisible' through the black-boxing process, and thus fallen victim to its own success.

Second, the pump is easier to become aware of in the public and private spheres than in research practice, primarily due to the nature of these activities. While the pump acted as a rather hidden research instrument in Hales's, Hauksbee's and others' investigations, and as a manufacturing tool for Monro, the intentions of using it in public and private settings was quite different. Publicly, the aim was to make the pump, and the phenomena that it could produce, as visible as possible to the audience, a role that also is reflected in the description of the pump in the sources. The role of the air-pump in Wright's painting is also obvious. A corresponding prominent position of the pump in the experimental accounts would simply have obscured the research results.

Finally, I will use these arguments to comment on van Helden's suggestion that the double-barrelled air-pump was perceived internationally as a demonstrational instrument only, while Senguerd's model from 1679, with a single, inclined barrel, came to represent utilitarianism. See Figure 55. Dutch and German instrument-makers took up Hauksbee's design, as well as produced Senguerd's version for more than fifty years. Helden has introduced the concept of 'stabilized meaning' of an artefact, which is reached when various opinions about an instrument converge to a commonly accepted and stabilized significance.[559] Helden also launched the concept of 'stabilized form', which happens when one design becomes dominant. One stabilized version of the continental air-pump was Senguerd's inclined cylinder; in Chapter 3 I showed that in England the air-pump stabilized with

[559] Helden (2002), 67-79.



**Figure 55.** Senguerd's inclined air-pump by Mussenchenbroek 1697. A symbol of Baconianism? Museo degli Strumenti per il Calcolo, Pisa.

Hauksbee's double-barrelled design of 1705. (I see Davenport's version as a variant of this principle design only).

Helden suggests that different meanings might have been attached to different variants. The meaning attached to the double-barrelled pump was that of a demonstrational tool. He argues, referring to Morton and Wess, that 'As such [as a demonstrational tool] it had been introduced, and as such it eventually became the international standard'.[560] Correspondingly, the inclined version was a symbol of Baconianism. Further, he claims that the purposes of these two variants differ at least as much as those of the terrestrial telescope and its astronomical counterparts. Here I do not agree. My survey above shows that the double-barrelled version was definitely used for utilitarian purposes, and perceived as such, at least in Britain. That natural philosophers and anatomists there thought of pumps of Hauksbee's design as teaching and entertainment-device only is therefore not correct. However, to know the full scope of research by the double-barrelled air-pump in this period, and of air-pumps generally, requires more work – a task that falls outside this study.

## Conclusion

In this chapter I have discussed research conducted with air-pumps. Such activities have not been well-known, as modern studies have concentrated on public and domestic applications of the device. I have examined two works in particular: Stephen Hales's studies of plants, animals, and air-filters; and Alexander Monro's production of pathological specimens. The air-pump was central to these undertakings, for Hales it was used in investigative and utilitarian experiments, while Monro applied it as a manufacturing tool. I have shown that these activities were much in the tradition of Hauksbee and the Pneumaticians. Further, I explained why these applications have until now been almost unknown, pointing to the effects of black-boxing and the different natures of research and demonstrations. Finally, I have commented on Helden's views on research versus demonstrations with the inclined and the double-barrelled air-pump, and claimed that the double-barrelled version cannot be seen as a demonstrational device only.

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[560] Morton and Wess (1993), 41-53.

# Thesis Conclusion

With *Leviathan and the air-pump* (1985) as the first chapter in the history of the English air-pump, this work presents new material for a sequel. However, the character of these two accounts are different. While Shapin and Schaffer focused on philosophical, sociological and political issues concerning Boyle's first and second air-pumps, I have concentrated on technical matters of Hauksbee's pump and its use in public and private demonstrations, and as a tool for research and practical applications. Shapin and Schaffer discussed matters of the air-pump in the period from 1658 to 1676, I have concentrated on the development and use of the device from 1699 to 1745. Not much concerning air-pumps took place in England in the period between Papin and Hauksbee.

Two relevant studies on natural philosophy in this period are Stewart's *The rise of Public Science* (1992) and Morton and Wess's *Public & private science* (1993). Stewart focused on social issues in the development and dissemination of knowledge and recognized the role of public experiments as counterparts to Newton's queries, but without mentioning a single experiment or instrument. On the other hand, Morton and Wess have given an excellent description of a series of instruments and experiments, and how they became used in public and private settings. However, Hauksbee, as well as the air-pump are only one among a number of other instrument-makers and instruments discussed.

My approach is different. I started off by examining Hauksbee's background and his first instruments, and learned about his customers. I went down to the level of nuts and bolts, gaskets and sealing wax, studying the development of technical

details from his first cupping utensils to his masterpiece, the double-barrelled air-pump. This enabled me to explain how he matured into one of the most important instrument-makers of the period, and why the air-pump became so central in disseminating natural philosophy to the public, as well as how it became a research tool.

The new knowledge obtained by this approach, that Hauksbee was a producer and seller of cupping utensils and instruments for use in anatomy before he started to make air-pumps, have made the mystery of him explicable. (I did not go much into his whereabouts before 1699.) There is in fact no mystery. Hauksbee did not emerge from obscurity, and the air-pump that he demonstrated at his entry to the Royal Society was a single-barrelled one, derived from cupping utensils. His classic, double-barrelled air-pump was not simply an improvement of Papin's, but a sophisticated machine where experiences from the single-barrelled one were fundamental. The crucial component in his cupping glasses, anatomical instruments and air-pumps was a valve, a small reliable contrivance that could 'let the air out, but not in again'. This device enabled him to build pumps that worked without the use of stopcocks, a characteristic and tedious element with Boyle's pumps. His cupping-devices required small gaskets and the knowledge of how to make such seals became subsequently transferred to the air-pump. Efficient seals did eliminate use of sealing wax, which was another distinctive feature of his air-pump.

By operating at this level, I also discovered the driving force behind the refinement of the valve: the dialog between Hauksbee and the buyers of his apparatus. Hauksbee's first cupping devices had some deficiencies and the customers complained. He answered with new and maintenance-free valves. Moreover, this led me into social aspects of the development of the air-pump. Some of his customers were surgeons, apothecaries and anatomists, professions that were represented among the members of the Royal Society. This suggests that the first contact between Hauksbee and that noble organization was based on his production, advertising and sale of cupping and medical instruments, and could have been made as early as 1699. He must have been a public figure and known to the Royal Society long before Newton picked him as his weekly demonstrator.

Moreover, cupping became practiced in the popular bathhouses (bagnios or hummums) that flourished in London in the period. These institutions, which were described as places for 'bathing, sweating and cupping' were among Hauksbee's customers, and they must have functioned as 'test-arenas' for his various models. The quality and success of Hauksbee's air-pumps, which had self-closing valves and sealing methods in common with the cupping-glasses, can thus be traced back to the commercial demand for cupping and blood-letting instruments in London in the early eighteenth century. Cupping and issues like 'air in the flesh' were also encountered in the public lectures that were given in the period, and cupping had thus a didactic role in teaching the public about the spring, pressure and weight of the air. The history of the English air-pump is the history of an instrument on its

way from natural philosophy to popular medicine – and back again. It had started off as a scientific instrument with Guericke and Boyle in the previous century. Hauksbee developed and refined the technology by producing cupping utensils, which in turn became used in his excellent air-pumps.

My approach enabled me also to monitor closely the process of the instrumental black-boxing of the pump. The conceptual black-boxing had taken place with Boyle, where it had become recognized as a device that could be used for producing novel matters of fact. The instrumental side of the process, however, where it became turned into a reliable and easy-to-operate instrument, took place with Hauksbee's single-barrelled model. By this contrivance, the attention was no longer on how to operate the pump, or on how it worked, but on the experiments that could be performed with it. Technically, the pump no longer represented a problem. Moreover, with Hauksbee's double-barrelled version, the black-boxed air-pump reached its stabilized form, a design which in principle was used into the twentieth century.

Further, the development of the air-pump can be described in four stages, seen from the point of how the access to the experimental space improved, and how this space became separated from the pumping functions. Also this was a process that became especially visible through my approach, learning how the operation of the pump became easier and less time-consuming by studying technical details. The pump developed from a stage where the pump-barrel and the receiver were integrated in one unit, through versions where the pumping facilities (like barrels, valves, racks, the crank, etc) were separated from the receiver. Here the receiver was open-ended and placed on a separate pump-plate, a solution that made experiments much easier. Hauksbee's single and double-barrelled pump belonged in principle to this stage. However, further developments of pneumatics turned the attention away from the pump itself and to series of specially-made receivers for various experiments. Many of Hauksbee's experiments were made in such receivers. The application is especially evident in Vream's instructions and depiction of fifty air-pump experiments.

Continuing along this line, it becomes clear that yet another stage could be outlined. We can no longer talk of pure air-pump experiments, but experiments where instruments became evacuated by the pump, and then separated and disconnected from it. Examples are Hauksbee's rotating globe (which I have replicated) and the hollow prism, which both could be connected to the pump to become evacuated, but worked as part of other experimental set-ups, having functions with, and without a vacuum inside.

By studying this technical/practical advance, it became clear that not only the pump, but also the vacuum-concept changed and became extended through this process. From Boyle and onwards, experiments had taken place in the receiver where the vacuum can be described as a special-made environment. However, with the pump as a supplier of vacuum for experiments performed elsewhere, vacuum

had become a parameter, ranging together with other input and outputs, and constants and variables in an experiment. The air-pump had become a tool, and the vacuum paradoxically thought of as an object.

A detailed survey of Hauksbee instruments has been undertaken to examine where they were used, and how they worked. In the public lectures, he used and demonstrated series of instruments in pneumatics, hydrostatics, optics, electricity and mechanics, being familiar with all these fields. His commercial product range was much smaller, however, comprised of cupping and anatomy utensils, single and double-barrelled air-pumps and condensing engines. Examining the various functions of these instruments, it became clear that those demonstrated in the public lectures and those made for sale overlapped mainly at one point: those regarding rarefying and condensing air. So what kind of instrument-maker was he? Scrutinizing the material shows that he never described himself as an instrument-maker of any kind, and he had few or no instruments in common with other makers. Neither did his contemporaries recognize him as a natural philosopher.

Hauksbee had several apprentices and followers who worked along similar lines. A detailed study of their instruments and their work, applying the same methods as above, makes it clear that Hauksbee and his followers can be distinguished from other instrument-makers in the period, and seen as a distinct group. Typical activities were production and sale of cupping utensils, anatomical instruments, and air-pumps with series of accessories. Most of them were engaged in public lecturing and had affiliations to the Royal Society. The prices of their products could be established as well. I have named this group, which was active from around 1700 till around 1745, the 'Pneumaticians'.

By further studies of their merits, it becomes clear that the Pneumaticians not only served a professional market (for example philosophers, procuring instruments for public lecturing or research), but also private individuals, doing experiments at home. Reading their writings from a technical point of view, it is evident that at least one of them (Vream's) was not written with professional users in mind. This particular text contains minute details on how to set up and perform series of air-pump experiments, as well as how to prepare for the next ones. It is clearly written for curious and moneyed individuals with time for trying experiments on their own.

This approach opened up a whole new dimension for the use of air-pumps and pneumatics in the period. The pump had entered the private sphere, becoming used as rational entertainment in homes. The situation depicted in Joseph Wright's painting of 1768, where a philosopher gives an air-pump demonstration in a private house, represents only one possibility of the period. Similar experiments, and even some much more advanced ones, must have been undertaken in private homes in London before 1720, and even without a professional instructor present. Moreover, the role and status of the air-pump at this stage becomes further evident in the

painting by Arthur Devis of 1742, where the air-pump is depicted together with traditional mathematical and optical instruments. The purpose of this picture was to signal cultural refinement and the intellectual aspirations of the sitters, and an air-pump, in fact not even the most technically advanced one, had become such a signifier.

The air-pump was also used for research and practical application in the period. However, evidence for such undertakings is rather obscure, and can only be found through close examination of the texts. Again, looking out for technical details proved to be the key. A common opinion among historians is that there was little or no research using air-pumps in the period. By studying several accounts about research on plants and animals, however, the air-pump emerges as a crucial, but hidden instrument. The eighteenth-century authors may now and then allude to the air-pump or to its implications, for example a vacuum, a suction, etc, but the intentions were clearly not to inform the readers about the pump, but to explain how new facts in botany and zoology were discovered. Only by perusing the texts did the pump become visible. It became clear that the air-pump was used in what we today call basic and applied research, and it was used as a manufacturing device for production of pathological specimens as well. My approach also explained why the air-pump has been regarded as an apparatus mainly for demonstration and teaching. The air-pump was a black-boxed instrument at the time; it had become improved and refined, and was simple to operate. There was no need for the user to worry about technical details, neither was it necessary to explain these to the readers. That is why it was mentioned only casually, and consequently remained out of sight for modern instrument-historians until now. The fact that the air-pump has been regarded as only a demonstrational instrument in this period, and not one for research, lies also in the different nature of these activities. To underline the importance of the pump, and to make it visible, was one particular intention with the lectures. A corresponding attention in the research-accounts would simply have obscured the main objectives. The air-pump was definitely used for research in England and Scotland in this period. My close reading of the texts shows that it was Hauksbee's double-barrelled version that was applied, and there are no clues that this version was associated with demonstrations of known facts only.

By my technical approach, I managed to show how Hauksbee turned the air-pump into a reliable and commercially available instrument. The pump became a black-boxed and socially recognized device with great potential in public and private demonstrations, in teaching and research. It became a symbol of status and refinement long before Wright depicted it as such. Through Hauksbee and the Pneumaticians, pneumatics had become established as a recognized field within natural philosophy, to a state with its own accepted methods, terminology, literature, instruments and craftsmen.

# Appendix
# Replicating the rotating globe

## Introduction

This appendix is about the replication of Hauksbee's rotating globe. 'Hauksbee's globe', originally built in 1706, is perhaps his most well-known contrivance after the double-barrelled air-pump, and is often depicted in works on the history of electricity and luminous phenomena. It played an important role in shaping his hypotheses on light and electricity, and was used for demonstrations in the Royal Society and in public lectures. See Figure 56.

The reworking of experiments is a powerful method for studying past science. It can be used together with traditional material for going deeper and seeing wider than what is possible by using, for example, written sources only. It can be used to study how theories and experimental routines developed, and has a pedagogical value in teaching modern historians about the material culture of the period. It can reveal important issues about instruments, experiments, social conditions and people involved, as well as 'tacit knowledge' required to obtain the given results. I replicated the globe to support my general studies of Hauksbee's experiments. So far, I have been able to rework several of them, for example the one on production of luminous matter in the evacuated globe. (Figure 45). However, the main objective for using it in my research on air-pumps was to let such practice clarify interactions and relationships between the pump and the globe, and how Hauksbee described such issues in his writings (See Chapter 4).

A replicated instrument can be seen as an interpretation of the common source-material itself. For information obtained from practice with such replicas to be trustworthy, a thorough description of the manufacturing process has to be available, including arguments for the various choices that have to be made during

the making. This text contains examples from the planning, manufacturing and testing of the device, together with arguments for my choices of the various technical solutions. I compare my replica to one by Professor Andrade, and explain why I in many cases applied different solutions than him.

## 1. Some methodological issues

For the two last decades, reworking of experiments has been used as valuable additions to the more classical approaches in history of science.[561] Otto Sibum's reworking of Joule's experiments about the relationship between mechanical work and heat,[562] and Peter Heering's replica of Coulomb's electrostatic balance have given interesting findings.[563] Joule gave his results as a relationship between numbers, and Coulomb as a simple equation, and thus performed *quantitative* experiments. Experience gained from reworking these experiments acted as complementary approaches, the methods developed in the process were particularly useful for the study of aspects of the experiments that could not be understood from the written material only. Klaus Staubermann, who rebuilt Zöllner's astro-photometer described reworking as helps to 'draw a more convincing trajectory through the existing sources, a trajectory which helps us to understand the making and success of the instrument'.[564]

Most of Hauksbee's experiments were of a different kind. They were performed in a period long before physical parameters were defined and quantified, and there are therefore no measurements that we can easily assess or rework. Information about luminous phenomena in Hauksbee's publications and contemporary literature must be regarded as subjective descriptions only, always influenced by the experiences, expectations, and comparison-background. Reworking as a method to study such *qualitative* experiments has rarely been used.

However, it became clear by making and using the globe that reworked, qualitative experiments could also yield valuable information. This is particularly clear in the present case, where practice revealed that Hauksbee must have undertaken crucial, tense and difficult operations (mounting of the globe) that were not mentioned in the published reports. My replica helped me to recreate the gestural knowledge required to perform the experiments.[565]

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561 P. Heering, F. Riess, C. Sichau, *Im Labor der Physikgeschichte* (Oldenburg, 2000).

562 Sibum (1995).

563 P. Heering, 'The Replication of the Torsion Balance Experiment. The Inverse Square Law and Its Refutation By Early18th-Century German Scientists' in *Restaging Coulomb*. Eds C. Blondel and M, Dörries (Firenze, 1994), 47-66.

564 K. Staubermann, 'Controlling Vision-The Photometry of Carl Friedrich Zöllner' (University of Cambridge. Ph.D. thesis, 1998),10.

565 Gestural knowledge is a term coined by Sibum, describing the 'complex skills and forms of mastery developed in real-time performances'. Sibum (1995), 76.

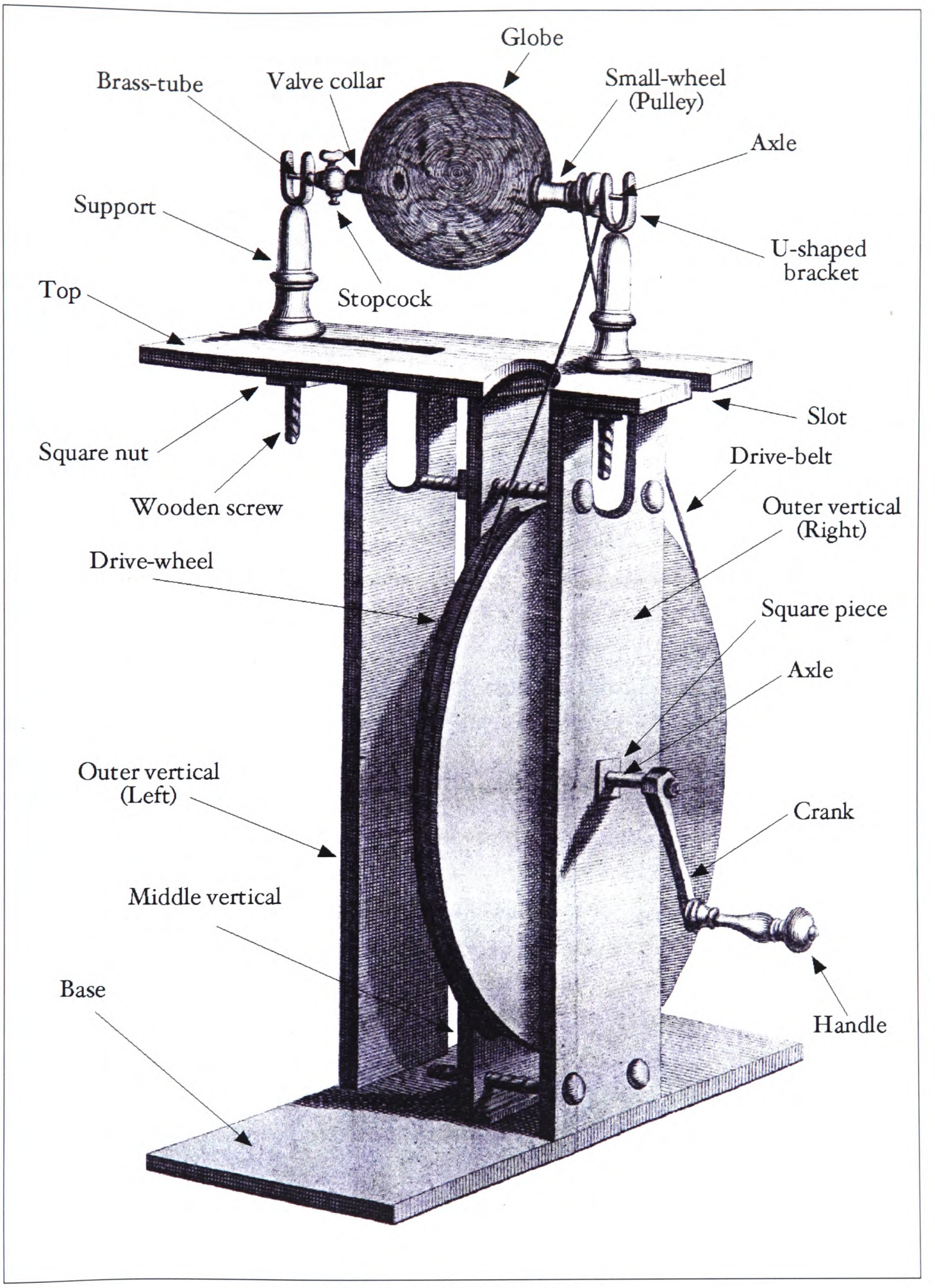



**Figure 56.** 'A new contrivance' (1706).
Hauksbee's rotating globe arrangement. *PME*, Tab VII.

## 2. Background

There already exists a replica of the actual machine, made by Professor E. Andrade (1887-1971) in 1927 (it was actually built by Mr. Robert Paul, Andrade's technician, but since it is known as Andrade's replica, I use this notation here).[566] The group at the University of Oldenburg who has specialised in reworking historical experiments has also made a replica of a 'Hauksbee-type' machine.[567] My machine, however, is different from these two.

It is possible to build replicas of old instruments in the physical sense only. The same effects might be demonstrated, but historical aspects like old manufacturing methods, use of materials, and developments of experimental skills will remain hidden, as well as sensuous experiences perceived by the operator and his audience. There is also a danger with this approach that the reworker will build his instrument to display only those functions he believes the original possessed. The replica will be a projection of ideas from before the work started, which will reduce the value of it as a historiographical tool. I see the Andrade machine as such an example, although it has a good visual resemblance to Hauksbee's. Andrade expresses no intentions of research with his replica, but rather used it for demonstration of interesting phenomena only. The Oldenburg-replica shows some physical functions of Hauksbee's and other, later, machines, but has a rather modern appearance.

However, in my work I wanted to include the historical dimension as well, and decided to build the machine by means of tools common in the actual period, and from original materials. A survey that I undertook showed that hand tools for wood and metal-work had in principle not changed significantly for the last 300 years, so I decided to use ordinary hand-tools whenever possible.[568] As pointed out by the Oldenburg group, misunderstandings might sometimes take place between the historian and the technician during replication work. This is not only caused by lack of technical knowledge among historians, but often due to different social attitudes, language, and outward appearances of both groups.[569] I have experienced similar problems between physicists and technicians during the manufacturing of modern scientific instruments. To avoid such issues, I decided to use my background as a laboratory technician and do all the planning, manufacturing, testing, and demonstrations of the replica myself.

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[566] Andrade, E. N, 'A Lecture with Experiments on Various Subjects', *Journal of Scientific Instruments*, Vol. IV. 5 (Feb. 1927), 130–7.

[567] Information from Internet. Only a picture and a short note are given: 'Elektrisiermaschine mit Reibkissen, Saugkamm und Konduktor nach F. Hawksbee, J.H. Winkler und Ch.A. Hausen zur Erzeugung und Ansammlung von Elektrizität (um 1740)'. http://www.uni-oldenburg.de/histodid/forschung/nachbauten/grelekmasch.htm

[568] J. Moxon, *Mechanick Exercises or the Doctrine of Handy Works* (London, 1703).

[569] Staubermann (1998), 55.

## 3. Planning

I made it a clear intention to make the total appearance of the replica as close as possible to the illustration given by Hauksbee, getting both proportions and overall size right. It can be objected that we cannot say if the picture (Figure 56) is a free artistic interpretation, or an attempt to give a more realistic image. There exist some sketches made by Hauksbee in the archives of the Royal Society in London.[570] These depict details of a few instruments and parts of the horizontal drive-wheel arrangement for the first chafing-experiments (Figure 16a, but without the pump-stand). There are no great differences between these sketches and the published versions, something that gives us less reason to distrust the given illustration. However, the best indication that Hauksbee's illustrations are relatively correct is the likeness between the illustration of the air-pump in his book and the real one kept at the Royal Society. Compare Figures 5 and 24. Nevertheless, the original machine must have disappeared long ago, and not even a comprehensive study of illustrations and texts could produce any definite evidence of its exact appearance, size and functions. Hauksbee had left no construction drawings. However, as a first step, I decided to build the replica based on the available material, without introducing modifications or additional components.[571]
A detailed study of the texts and illustrations was undertaken. This included both editions of Hauksbee's book, *Physico-Mechanical Experiments*, his 50 articles in the *Philosophical Transactions*, and the Hauksbee papers in the Royal Society. Hauksbee's air-pump in the possession of the Royal Society was also examined, looking for details on components and assembling techniques which might be useful during the replication process. The actual machine, called 'a new contrivance', was first described in an article in *Philosophical Transactions* in December 1706, and later in his book (1709), which also gives an illustration. (Figure 56).[572] The machine is seen in perspective, from an angle a little above and partly sideways to the machine. This view reveals many details, like the glass-globe with stopcock and suspension brackets, the drive-wheel, and the wooden structure with base, verticals, and top. The last one is supplied with longitudinal slots for adjustment of the supports, thus enabling the use of different sized globes and cylinders. It is not clear, however, how the wheel was fastened to the axle, or how the valve collar and pulley were attached to the globe.

An early step was to 'disassemble' the machine mentally and make sketches of all the individual components. This included every part of the wooden structure, as well as the drive-wheel, crank and handle; the globe, supports and U-brackets; the

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[570] The Royal Society, 'The Classified Papers', Cl.P. no. 18 (London, 1704 -1713).
[571] The fact that I copied details that were not directly necessary for the function of the machine, like ornaments on supports and handle, must be explained by the professional pride of the craftsman in me.
[572] *PME*, Tab. VII.

stopcock with all its small parts; wooden screws and nuts, and finally some design ideas for the drive-wheel hub. The original machine must have consisted of more than a hundred different parts, including screws, nuts and driving-belt clip.

My next move was to find a way to transfer Hauksbee's original perspective picture into several modern construction drawings, showing all the components in the right shape, size, and position. An old technique for drawing pictorial perspective, for example used by Dürer and da Vinci, is to place the object in front of a transparent glass-plate, on which the artist draws the outline of it, looking through a fixed eyepiece.[573] After some experimenting with diverse methods, I decided to start the process of transforming the illustration into a three-dimensional object (the replica) in a similar manner. However, in this case there existed an image, but no object. Therefore, I had to go the other way around. First, I mounted a transparent photocopy of Hauksbee's machine in a vertical position. I then gradually built up a small plywood model by components that were placed so that they should fit into the transparent image when viewed from a fixed point on the opposite side. See Figure 57.

The fact that the pictorial-perspective method would not automatically give an image like the one perceived directly was pointed out early in history.[574] The image of an object perceived by the eye and mind is always a sum of several more or less similar impressions, obtained by looking at it from slightly different angles, head movements, in different light conditions, and so on. The advantage from watching an object through a fixed eyepiece for depicting it on a screen is thus accuracy, but often with fewer details compared with illustrations that are more artistic. Halfway through the making of the small model, I realised that the original figure could *not* have been drawn following the method above alone. Assuming that the original base was a regular rectangle, and the three verticals were of equal size and directly opposite to each other, it was impossible to make a horizontal and rectangular top board 'disappear' into the image

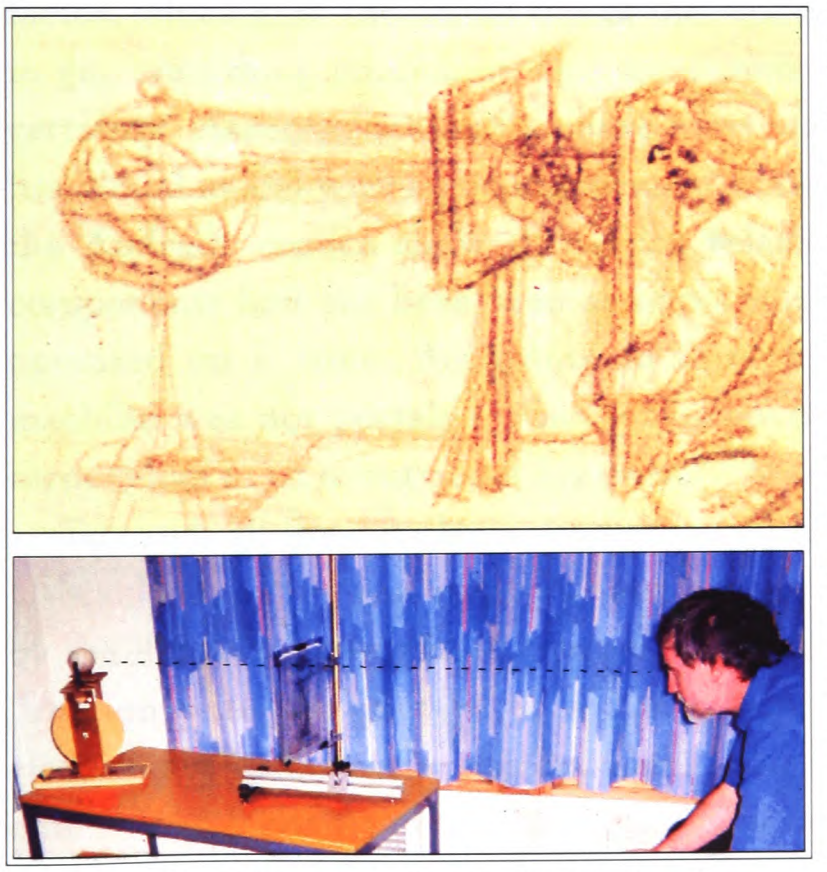


**Figure 57**. Above: L. da Vinci, 'Design for a perspectograph', c. 1480-82. *Codex Atlanticus*, 5 r, Biblioteca Ambrosiana, Milan.
Below: My way. The transparent image is seen in the middle. The small plywood model to the left was formed to fit into the image when viewed from a certain point. Photo: University of Tromsø (2000).

[573] E. S. Ferguson, *Engineering and the mind's eye* (London, 1992) 77-82.
[574] V. P. Zubov, *Leonardo da Vinci.* (Cambridge, Mass. 1968), 142.

like the base did. In addition, several smaller parts like the valve, supports, and pulley refused to fit with the positions in the image if they were to be functional. However, if the point of view were slightly adjusted when these components were sighted, their relative size and form could be found. I concluded that the illustration had to be a little distorted, especially the upper part, but on the other hand gave good information about the original object. The relative size of the different components could be determined, and their positions came naturally from their functions.

I saw the overall size as significant, because it would become important for the man/machine relationship, and therefore all the possible functions of the machine. For example, Hauksbee was concerned about the surface velocity of the glass globe, and I had to come as close as possible to his values.[575] This is a parameter that depends on the individual sizes of the rotating components, so a correct scaling factor between the model and the replica had to be found. He did not give any dimensions of the actual machine, but wrote that the diameter of the big horizontal drive-wheel on his first chafing set-up was 23", and the small one 1.5" in the grooves.[576] These numbers were about 2.5 times greater that those of the wheels on my small model. Assuming similar wheels on all the machines, a scaling factor of 2.5 was chosen. All dimensions on the plywood model were multiplied by this factor, which gave the actual size of the replica parts. It was not possible, however, to get everything consistent, and some dimensions could not be determined with certainty. Assumptions and compromises were necessary in some cases to get a functional model with a good agreement to text and illustration. An examination of the Andrade replica showed that the relative size and shapes of the individual components had not been seen as important. It is smaller than mine, and can be operated on a table. According to Joseph Priestley (1733-1804), Hauksbee's machine was not portable. Another inconvenience was that the operator (wheel turner) had to sit to carry out his work.[577] See Figure 44.

To catch all the details on smaller components like the crank, handle, supports, U-brackets, pulley and stopcock, etc; pictures of them were scanned and enlarged by the illustrator program Canvas 6. The outline was recorded using a multi-layer function with the picture as a background, and manipulated in 3-D to give electronic versions of the objects. Once these matched the original components, the dimensions were fixed and used for construction drawings. As a final test, all components modelled in 3-D were put together to form a computerised model of Hauksbee's machine, which was compared with the original engraving. See Figure 58. A few small corrections had to be made before a complete set of construction drawings were produced for use as blueprints during manufacturing.

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[575] *PME,* 26.

[576] *PME,* 25.

[577] J. Priestley, *The History and Present State of Electricity, With Original Experiments* (2 vols, London, 1775), ii, 106. Priestley discusses several electrical machines from the first half of the eighteenth century.

## 4. Manufacturing

On Andrade's model, wood and metal work, as well as glassblowing, had been performed by twentieth-century machine tools, something that clearly influenced its appearance and functions.[578] Since a study of Hauksbee's workshop, methods and tools was included in my project, the use of materials and tools similar to his would serve as a good introduction, as well as give a more 'true' replica in the end.

As has been common in other reworkings, it was not possible to reconstruct the apparatus in full.[579] Compromises became necessary, something that forced me to assess all aspects and functions, and judge which were crucial for the outcome of the experiments. The advantage of using replications as a complementary source became evident from these assessments, as many details that would have easily been overlooked in studies based on texts only were discovered.

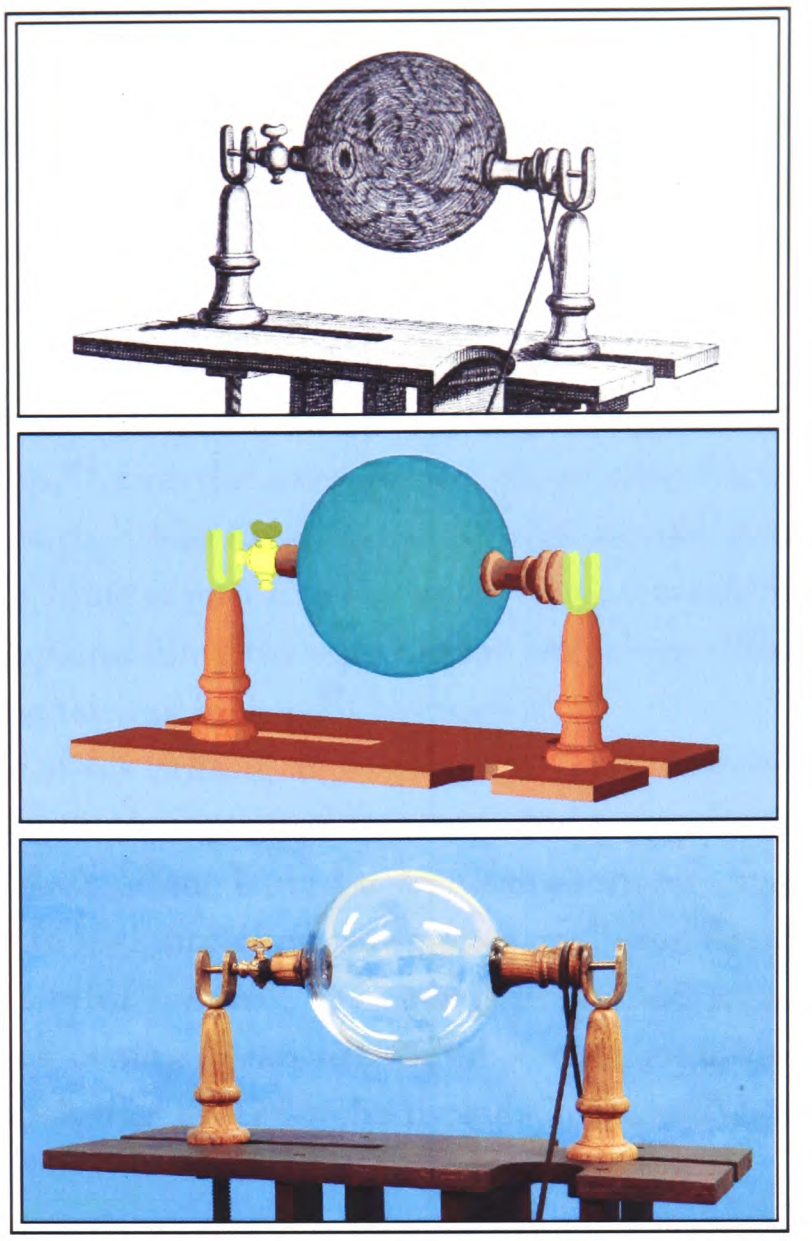


**Figure 58.** The original, the computerized, and the replicated Hauksbee-globe.

At least two of Hauksbee's pumps were made of walnut and I chose that for the replica.[580] A thickness of 3/4" or 19 mm was used for the base, verticals and top, which relates well to the general size of the machine, as seen from the illustration. The raw wood materials were of course cut by machines, but in the process of transforming the planks into useful components for the replica, I used hand tools only, some of them in fact made by myself.[581] Sawing, planing and turning were done the traditional way. No hand, foot, or assistant-driven lathe was available, so I used a simple 'do-it-yourself' lathe run by an electric drill at low speed, and applied traditional, hand-held cutting tools. A similar arrangement was used for turning the

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[578] This comes clear with the first look at the machine by a trained eye.

[579] This is pointed out by several reworking historians. See: Sibum (1995), 76; Heering, (1994), 52; and Staubermann (1998), 38.

[580] Andrade (1927), 137. (This pump is kept by the Royal Society, see Figure 99); G. L'E. Turner, *Scientific instruments, 1500- 1900. An introduction.* (London, 1998), 71. (This pump is in a private collection, see Figure 99).

[581] Made as part of my training as a mechanic 40 years ago.

big drive-wheel, which was laminated and glued together from several pieces to avoid warping. The type of lathe used by Hauksbee is not known. It could either have been turned by one of his apprentices, or for example by a treadle arrangement. I found that one major difference between lathes with fixed cutting tools (like modern lathes for metal) and those with hand-held tools is the accuracy of the roundness obtained on the work-piece.

The U-brackets and the valve were made from brass, the other metal parts from iron. I cut out the pieces with a hacksaw and shaped them by filing and grinding. Hauksbee had a forge in his workshop,[582] and the axle for the drive wheel had presumably been hammered into the shape. I had no access to a forge myself, and chose the slow and cumbersome way of filing it into a round cross-section, while it rotated slowly in the lathe, and chiselling and filing the square part into shape. The crank, however, was made in the traditional way by a local blacksmith.

Hauksbee does not give any details of his drilling arrangements, but it is clear that he was able to achieve a reasonably high degree of accuracy, for example on some components on the air-pump. Most often, I used a traditional auger or a hand-held, low speed, electric drill. When high precision was necessary I used fixed drilling, which means that the upper end of the drill or auger is prevented from moving sideways during operation. Such arrangements are found in contemporary literature, and I used it to obtain perpendicular holes for the threads in the wooden square nuts.[583]

The two supports holding the U-brackets were made from ash, with a wooden screw inserted in the bottom to fix them to the top-board through the slot. I had to spend some time developing skill for achieving a satisfactory alignment of the bracket, support, and screw, without using modern, high-precision machines. In this case, the pedagogical value of the replication became evident. Similar skill is probably present among private hand-tool enthusiasts today, but the method is not necessarily part of the professional programme for young mechanics.

Moreover, the depicted wooden screws for keeping the left and middle vertical together, and also those on the supports, have a much higher pitch than normally found on newer wooden screws. In this case I assessed the pitch here not to be essential, and since the principle for making such screws has not changed, I chose a traditional, and commercially available, hand-held cutting tool. I made the screws and nuts from white beech, 19 mm, (or 3/4") thick and with a pitch of 4 mm.[584] If the given illustration is correct, the original pitch can be estimated to about 12 mm.

Hauksbee shows no details of the wheel-axle suspension, but the square piece on the outer vertical gave a hint. I interpreted it as a bearing, and similar pieces of iron, with a hole for the axle, were fixed on both sides of the outer vertical, and on

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[582] On one occasion he used a 'red hot iron' in an experiment, something that only could have been possible with a forge close by. See *PME*, 67.

[583] R.A. Salaman, *Dictionary of wood working tools c. 1700-1970 and tools of allied trades* (London, 1989), 189-90.

[584] Beech was often used for such applications, because of its hardness.

the middle one. The drive-wheel was fastened to the square section of the axle, through a corresponding opening in the centre. To strengthen the connection, I attached two thick iron pieces, fitting over the square parts, onto each side of the wheel. In this way I achieved an easy-running wheel assembly, but not so smooth and quiet as Andrade's, which used ball-bearings.[585]

The main components of the machine are of course the glass-globe and the stopcock. Andrade had used a machine-made globe. (It is almost a perfect sphere). Following my principle about using old techniques only, I needed a globe made by hand (and mouth). I had neither training, nor facilities to do this myself, and had, like Hauksbee, to procure it from a specialist.[586] The globe had to be supplied with two diametrically opposite necks, one with an opening for pumping to support the valve collar and pulley. Hauksbee mentions flint glass several times, and it is likely that this was used for the globe. I chose a quartz glass with a high content of lead.[587] However, it became clear that the skill of blowing spherical shaped glass vessels of this size is not present with all modern glassblowers. The job was first given to one working for scientists, who gave up after some unsuccessful attempts, and offered me a factory-made perfect glass-sphere instead. I declined, and asked an artist to do the job. Shortly after, he presented a well-made globe about 20 cm in diameter, almost spherical, but of uneven wall thickness and with the two necks a little too big, at a cost of approximately 1/3 of the whole project.[588] This was the best I could get from a process close to early-eighteenth century glassblowing.[589]

Not many details can be obtained about the valve-collar and pulley in the original illustration. Such items were often made of brass and attached to the glass components by sealing wax. Several examples of this can be found in Hauksbee's illustrations,[590] and on one occasion, he talks of 'fastening the brass-work to the glass'.[591] But in this case I interpreted the small wheel (pulley) to be a wooden cylinder with a groove for the drive belt near one end, and a collar for attaching it to the globe at the other.[592] Also the valve collar, hardly seen through the globe, was believed to be out of wood, and I made these two components from ash, shaped like the original. Andrade had used brass, however, with the valve screwed onto the collar by a modern flange system. Hauksbee mentions sealing wax and pitch for such applications. The exact composition of his sealing wax is unknown, so I used pitch, or black shoemaker's tar to fasten the valve-collar and the pulley to the glass globe. The valve was attached to the collar through a short brass tube, applying

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[585] They were hidden inside the verticals.

[586] Hauksbee writes that he had to procure the glassworks. *PME*, 53.

[587] Lead Crystal, type 16 G. Appr. 25% PbO, 58% $SiO_2$.

[588] He later admitted that he had succeeded first on his third attempt, but I had to pay for all of them.

[589] S. Lindquist, 'A Wagnerian Theme in the History of Science' in T. Frängsmyr (ed.), *Salomom's House revisited* (Canton, MA, 1990),167.

[590] *PME*, Tabu. III, Fig 2, 3, 5.

[591] *PME*, 167.

[592] 'The small wheel' is Hauksbee's own term. *PME*, 23.

pitch as both glue and sealing agent. In this way I strove to get closer to the original construction than Andrade, who had used modern, stable glue, and most likely rubber gaskets for the valve. From my previous experiences as a lab technician, I knew perfectly well that components like sealing agent and gaskets are decisive for the function of vacuum-equipment. Modern components here would certainly distort the historical aspects of my replica.

The alignment of the valve, the globe and pulley was difficult. The original illustration shows that the globe is rather off-axis. I interpreted it as an artistic distortion, and tried to achieve a better alignment. However, it was not possible to achieve a perfectly aligned, wobble-free globe. First, the hand-made globe itself was not a perfect sphere, and the two necks were not completely aligned as well. I tried to adjust for this by making the openings in the valve-collar and pulley a little bigger than the glass-necks, which gave room for sideways adjustments when glued onto the necks with hot-melted tar. The final result became a functional, well spinning globe, but about 3 mm off-axis, and with an appearance not so different from the original. See figure 59.

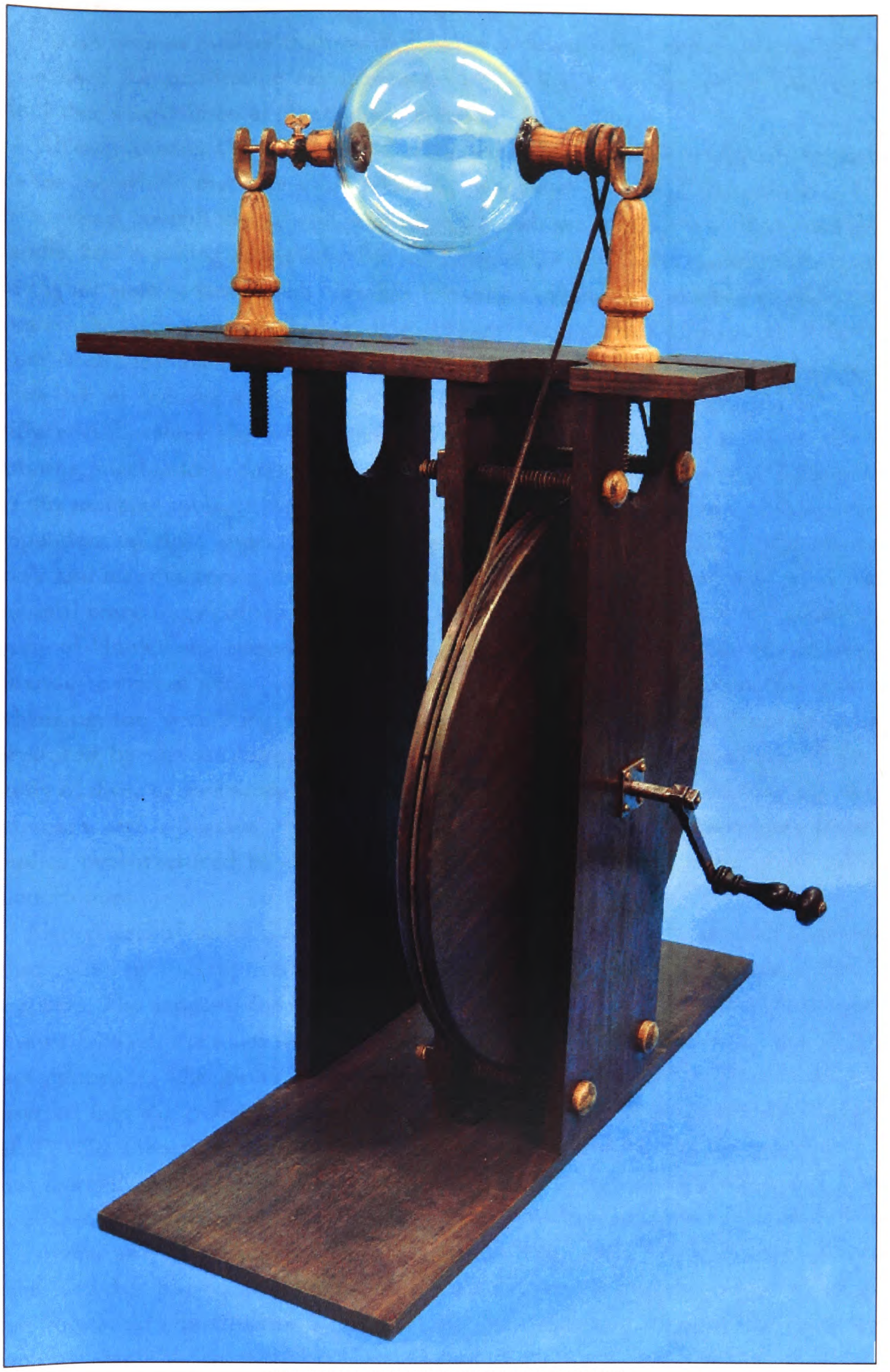


**Figure 59.** The replicated globe-machine.
Globe diameter: 20 cm. Overall height: 105 cm.
Tromsø and Oxford, 2000. Photo: University of Oxford.

## 5. Testing

It soon became evident that the replication of this machine, which originally had been used for qualitative experiments, yielded much for the understanding of Hauksbee's experimental practice and results.

Already during the first tests, I recognised that the eccentricity of the globe makes the whole machine vibrate during operation. The small imbalance of the drive wheel contributes as well, and together with the rattling from the crank and handle, and creaking of the wheel-axle, the machine gives off a considerable noise. At higher speeds, the machine shakes so much that the operator has to place one foot on the base to stop it from sliding sideways on the floor. This is very different from Andrade's machine, whose well-aligned and wobble-free globe and balanced drive-wheel secures a convenient operation at a much lower sound level. The difference between the two replicas therefore lies mainly in the accuracy of the rotating, mechanical components, or between achievable precision from hand tools versus machine tools. It shows that the final outcome of a replication process is not dependent on close appearance and original material only, but also on the applied tools and manufacturing techniques. In this case, I will argue that noise caused by 'natural inaccuracy', obtained by use of original tools, is crucial for understanding some of Hauksbee's experiments. In one instance, he reported that the luminous phenomena were accompanied by a considerable noise, 'not much like that of wheezing, tho' something smarter'. The sound was distinguishable from the noise produced by the machine, 'which notwithstanding was not a small one'.[593] In a study of these experiments, where Hauksbee used noise from the working engine to compare and 'calibrate' the intended experimental results, experiences from a replica manufactured by original methods count more than those achieved by modern ones.

Also practical tasks like preparing the machine for demonstrations became illuminated by this replication, for example by the adjustment problems of the U-brackets. The supports for the U-brackets are fastened to the top board by wooden screws through the axial slots, making possible the use of differently sized globes and cylinders. The globe is suspended in the right U-bracket by an iron axle inserted into the pulley, likewise by a brass tube fastened to the stopcock at the left.[594] When the globe is mounted on the machine after pumping, the pulley-axle is first inserted into a hole in the fixed U-bracket to the right. The globe is then kept in position with one hand, while the left support is moved towards the right with the other, until the brass tube slides into the hole in the left U-bracket. I soon perceived that this was a tense and delicate operation. It requires careful sideways and rotational adjustments of the left support until both axles of the globe are running smoothly in their brackets, before the square, wooden nut under the support can be tightened. A slight misalignment will easily lead to jamming of the

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[593] *PME*, 65-6.

[594] The globe is pumped through this tube.

axles during rotation, and thus exert dangerous stress on the collars, pitch, and glass. This procedure is especially stressful during public demonstrations, holding the fragile glass-globe in one hand, trying to get the support into place with the other, often with reduced room lighting, and with the onlookers following every movement you do.

I needed a lot of practice before the task of removing, pumping and mounting the globe onto the machine developed into a routine. Still, a high degree of caution is required. Hauksbee writes nothing about this in his accounts, but that he must have experienced the same kinds of problems is strongly suggested from practice with my replica. The task of putting an evacuated globe onto the machine is a first, important step towards a successful demonstration. Hauksbee did not give any details here, but the replica made me aware of the problem. Traditional sources would not have been sufficient here.

## Conclusion

The issues discussed above are some examples from the reworking process. Similar matters were the making of the stopcock and the frame, as well as discussions about their functions. According to J. Frerck, who introduced the term 'functional plausibility', a reconstructed instrument should not contradict historic technology without a good reason. When the functions of the historic, and of the replicated instrument match, the results from the reworking process can be seen as functionally plausible.[595] This is what I have obtained with my efforts, something that proved true when I used the machine to rework Hauksbee's globe-experiments.

[595] J. Frerck, *Die Zahnradmethode zur Messung der Lichtgeschwindigkeit*, Diplomarbeit an der Universität Oldenburg (Oldenburg, 1996), 60.

# Bibliography

## 1. Manuscripts and archival material


### 1.1 The Royal Society, London

Bacon, J. 'Fellows', Ref no EC/1750/14.
Papin to Sloane, Dec 31, 1711. 'Early letters' EL/PI/93.
'The Classified Papers', Cl.P (London, 1660-1741).
'The Journal Book', JBC 10. (London, 1702-1714).

### 1.2 Bodleian Library, University of Oxford: John Johnson Collection

Hauksbee, F, [Senior] and Hodgson, J, *Hydrostatical and Pneumatical experiments,* (London, Undated). Leaflet. Entertainments folder 7. [The syllabus is undated, but a publishing year of 1708 can be estimated from the content].

### 1.3 British Museum, The collection of Sir Ambrose Heal

Davenport, S, 'All Machines (...)', Trade card (London 1721). Heal: 105. 34.

### 1.4 The Medical Library, University of Otago, New Zealand

Monro Alexander Primus, *A Treatise on The Anatomical Encheiresis Or manual Part of Anatomy*. (1747). Ms. 169 [Handwritten, unpublished. Transcribed by P. A. G. Monro. (1997)].

### 1.5 The Drapers Company of London

Boyd's Roll.

## 2. Printed primary sources

### 2.1 Books


Adams, G, *Micrographia Illustrata* (London, 1746).
Bartholin, C, *Diaphragmatis Structura Nova* (Paris, 1676).
Blancard S, *Anatomia Reformata.* (Amstelodami, 1688),
Boyle, R, *The Works of Robert Boyle.* Hunter, M. and Davis E. (eds.) (London, 1999).
Campbell, R, *The London Tradesman* (London, 1747).
Cotes, R, *Hydrostatical and Pneumatical lectures*, Smith, R (ed.) (Cambridge, 1747).
Cowper, W, *The Anatomy of the Human Body* (Oxford, 1698).
– *Mytomia Reformata, or an Anatomical Treatise On the Muscles of the Human Body With an Introduction Concerning Muscular Motion* (London, 1724).
Croker, H, *The Complete Dictionary of Arts and Science* (London, 1764).
Culpeper, N, *Two Treatises, The First of Blood-Letting, and The Second of Cupping and Scarifying* (London, 1672).
Cuthbertson, J, *Description of an Improved Air-pump* (Amsterdam, 1787).
Davenport, S, *A Description of the New Invented Table Air-Pump* (London, 1737).
Derham, W, *Physico-Theology* (London, 1744).
Desaguliers J. T, *Physico Mechanical Lectures* (London, 1717).
– *A Treatise of Hydrostaticks* (London, 1718).
– *A Course of Experimental Philosophy* (2 vols, London, 1734, 1744).
Drake, J, *Anthropologia Nova* (London, 1707).
– *Antropologia Nova* 2nd ed (London, 1717).
Ferguson, J, *Lectures on selected Subjects* (London, 1776).
Genga, B, *Anatomy Improved and Illustrated* (London, 1723).
Graaf, De R, *De Usu Siphonis in Anatomia* (Leiden, 1688),
Gravesande, s', *Physices Elementa Mathematica* (2 vols, Leiden, 1720-1).
Greenhill, T, *Nekrophelia, or, The art of embalming* (London, 1705).
Grew, N, *Musæum Regalis Societatis. Or a Catalogue & Description of the Natural and Artificial Rarities Belonging to the Royal Society and Preserved At Gresham College* (London, 1681).
Hales, S, *Vegetable Statics* (London, 1727). Reprint (London, 1969). All references are to the new edition.
*Haemastaticks* (London 1733).
– *Philosophical experiments* (London, 1739).
Halley, E, *Correspondence and Papers of Edmond Halley,* MacPike, E, (ed.) (Oxford, 1932).
Harris, J, *Lexicon Technicum,* 1th ed (London, 1704).
– *Lexicon Technicum* 5th ed (London, 1737).
Hatton, E, *A New View of London* (London, 1708).
Hauksbee, F. [Senior], *Physico-Mechanical Experiments On Various Subjects. Containing an Account of Several Surprizing Phænomena Touching Light and Electricity, Producible On the Attrition of Bodies* (London, 1709, 19).
Hauksbee, F. [Junior], *The Patch. A Heroi-Comical Poem* (London, 1724).
– *Proposals for making a large reflecting telescope* (London, 1730).
– *A Further Account of the Effects of Mr. Hauksbee's Alternative Medicine* (London, 1743).
– and Whiston, W, *A Course of Mechanical, Magnetical, Optical, Hydrostatical, and Pneumatical Experiments* (London, 1714). [The book is undated, but a publishing date of March 1714 can be set from the newspaper-advertisements].
– and Shaw, P, *An Essay for Introducing a Portable Laboratory* (London, 1731).

Heister, L, *A General System of Surgery* (London, 1768).
Hills, M, *A Short Treatise On the Operation of Cupping* (London, 1832).
Hooke, R, *Philosophical Experiments* (London, 1726).
Hunter, M. and Davis E. (eds.), *The Works of Robert Boyle* (14 vols, London, 1999).
Hunter, W, *Two Introductory Lectures* (London, 1784).
Hutton, C, *A Mathematical and Philosophical Dictionary* (2 vols, London, 1796).
Johnson, S, *A dictionary of the English language* (London, 1755, 73).
Kepar, G, *The Gardener's Almanack for the Year of our Lord 1702* (London, 1702).
Mapleson T, *A treatise on the Art of Cupping* (London, 1813).
Martin, B, *Essays On Electricity* (London, 1746).
– *The Description and Use a New, Portable, Table Air-pump* (London, 1766).
Middleton, E, *The New Complete Dictionary of Arts and Science* (London, 1778).
Monro, A, Primus, *A Treatise On Comparative Anatomy* (Edinburgh, 1783).
– 'The Professor's Daughter. An Essay On Female Conduct' (1739). Supplement no 2, in *Proceedings of the Royal College of Physicians of Edinburgh*, vol. 26, no. 1 (Edinburgh, Jan. 1996).
Monro, A, Secundus, *The Works of Alexander Monro* (Edinburg, 1781).
Moxon, J, *Mechanick Exercises or the Doctrine of Handy Works* (London, 1703).
Newton, I, and Cotes, R, *Correspondence of Sir Isaac Newton and Professor Cotes* (London, 1850).
Newton, I, *Opticks*, 4th ed (London, 1730). Reprint London (1979).
– *The Correspondence of Isaac Newton*, Hall, R, et. al (eds.) (Cambridge,1959-1977).
Nichols, J, *Illustrations of the Literary History of the eighteenth century* (8 vols, London, 1817).
Papin, D, *A continuation of the new Digester of Bones* (London, 1687).
Paré, A, *An Explanation of the Fashion and Use of Three and Fifty Instruments of Chirurgery* (Edinburgh, 1634).
Parker, G, (ed.), *The Double Ephemeris for the Year of our Lord 1703* (London, 1703).
Priestley, J, *The History and Present State of Electricity, With Original Experiments* (2 vols, London, 1776).
Rackstrow, B, *Miscellaneous Observations, Together With a Collection of Experiments On Electricity* (London, 1748).
– *A Brief Description of Those Curious and Excellent Figures of the Human Anatomy in Wax* (London, 1790).
Ramelli, A, Le diverse et artificiose machine (Paris, 1588). English translation, *The various and ingenious machines* (New York, 1976).
Ribright, T, *A Description of the Air-Pump Made in Form of a Table* (London, 1757).
Sharp to Flamsteed, 25 Oct. 1704, in Forbes, E, (ed.), *The correspondence of John Flamsteed* (3 vols, London, 2002), iii, 105-6.
Sprat, T, *History of the Royal Society* (London, 1667; Reprint St. Louis, Mo. 1959).
Staples, J, *A Few Practical Observations On the Art of Cupping* (London, 1835).
Uffenbach, Z. von, *Herrn Zaccharias Conrad Von Uffenbach Merkwürdige Reisen Durch Niedersachsen, Holland Und Engelland* (Ulm, 1753, 4).
– *London in 1710, From the Travels of Zacharias Conrad Von Uffenbach*. Quarrell, W. H, and Mare, M. (eds.) (London, 1934).
Vream, W, *A Description of the Air-Pump, According to the Late Mr. Hawksbee's Best and Last Improvements* (London, 1717).
Ward, E, *The London Spy, the Vanities and Vices of the Town Exposed to View (1703)* (London, 1703; Reprint London, 1927).

White, T, *A Catalog of Optical, Mathematical and Philosophical Instruments* (London, 1838).
Woodall, J, *The Surgeons Mate, or, Military & Domestique Surgery*, 2nd ed (London, 1639).
Worster, B, *A Compenious and Methological Account of the Principles of Natural Philosophy* (London, 1722).

**2.2 Articles**

'A Continuation of New Experiments (...) The Second Part', by Robert Boyle. Review in *Weekly Memorials for the Ingenious* London, 11 Dec, 1682), 335-43.
Derham, W, 'Experiments About the Motion of Pendulums in Vacuo', *PT*, vol. 24 (1704), 1785–9.
- 'Experiments Concerning the Vibrations of Pendulums', *PT*, vol. 39 (1735), 201–3.
Gray, S, 'Two Letters from Mr. Stephen Gray', *PT*, vol. 37 (1731-2), 397-407.
- 'A letter from Mr Stephen Gray to Dr. Mortimer', *PT*, vol. 37 (1732-32), 285-91.
Hauksbee, Francis [Senior], 'An Experiment, to show the Cause of the Descent of the Mercury in a Storm', *PT*, vol. 24 (1704-5), 1629-30.
– 'An Experiment Made at a Meeting of the R. Society (...) of Firing Gunpowder', *PT*, vol. 24 (1704-5), 1806-7.
– 'An Account of an Experiment (...). To Try the Quality of Air', *PT*, vol. 24 (1704-5), 1807-9.
– 'An account of an Experiment (...) upon the Propagation of Sound', *PT*, vol. 24 (1704-5), 1902-4.
– 'An Account of an Experiment (...) Touching the Diminuiton of Sound', *PT*, vol. 24 (1704-5),1904.
– 'Experiments on the Resilition of Bodies in Common Air, in Vacuo and in Air Condens'd', *PT*, vol. 24 (London, 1704-5), 1946-8.
– 'Several Experiments on the Mercurial Phosphorus', *PT*, vol. 24 (1704-5), 2129-35.
– 'Several Experiments on the Attrition of Bodies in Vacuo', *PT*, vol. 24 (1704-5), 2165-75.
– 'An Account of an Experiment Made before the Royal Society.' in *PT*, vol. 25 (1706-7), 2277-82.
– 'An Account of an Experiment (...) Touching the Extraordinary Electricity of Glass', *PT*, vol. 25 (1706-7), 2327-35.
– 'An Account of an Experiment (...) of separating Two Hemispheres', *PT*, vol. 25 (1706-7), 2415.
– 'Several Experiments Touching the Seeming Spontaneous Ascent of Water', *PT*, vol. 26 (1708-9), 258-266.
– 'An Account of some Experiment touching the keeping of fishes in Water.' *PT*, vol. 27 (1710-12), 431-4.
– 'Experiments concerning the Effects of Air Pass'd through Red Hot Mettals, &c', *PT*, vol. 27 (1710-12), 199-203.
Houghton, J, 'Variuos Articles Concerning Natural Philosophy', in *A Collection for Improvement of Husbandry and Trade*, vol. 1-20, (1692-1703).
Huygens, C. and Papin, D, 'A Continuation of the Experiments', *PT*, 10 (1675), 492–5.
– 'Some Experiments Touching Animals', *PT*, vol. 10 (1675), 542–8.

Luffkin, T, 'An Extract of a Letter from Mr. Thomas Luffkin of Colchester', *PT*, vol. 21 (1699), 287-8.
– 'A Letter from Mr. Thomas Luffkin to Dr. Sloane', *PT*, vol. 21 (1699), 408–10.
– 'Let *A B*, be a hollow Brass Cylinder', *The Philosophical Transactions Abridged*, vol. III, (1749), Paragraph XXIX, 261–2.
Lowthorp, J, 'An experiment of the Refraction of the Air', *PT*, vol. 21 (1699), 339-42.
Smeaton, J, 'A Letter from Mr. J. Smeaton to Mr. John Ellicot, FSR, concerning some improvements, made by himself in the air-pump', *PT*, 47 (1753), 415–27.
Wilson, G, 'On the Early History of the Air-pump in England', *The Edinburgh New Philosophical Journal*, XLVI (1849), 330–54.
Wimmerstedt, J, 'Geshichte Der Luftpumpe', *Wissenchaftliche Zeitchrift*, 33, Part 2 (1989), 116–26. (Originally published in Uppsala, 1734).

### 2.3 Newspapers

*The Post Man, And the Historical Account, etc* (London, 1699-1706).
*The Englishman. Being the sequel of the Guardian* (London, 1714).
*The Flying Post: or, POST-MASTER* (London 1699).
*The Daily Courant* (London 1704-20).

## 3. Printed secondary work

### 3.1 Books

Acierno, L. J, *The History of Cardiology* (London, 1994).
Allan, D. and Schofield, R., *Stephen Hales, Scientist and Philanthropist* (London, 1980).
Anderson, R. G. W; Bennett, J. A; and Ryan, W; *Making Instruments Count: Essays On Historical Scientific Instruments Presented to Gerard L'Estrange Turner* (Aldershot, 1993).
Anderson, R. G. W, *The Playfair Collection* (Edinburgh, 1978).
Audry, D, *Bloodletting Instruments in the National Museum of History and Technology* (Washington, 1979).
B. Lillywhite, *London Coffee Houses* (London, 1963)
Banfield, E, *Barometer Makers and Retailers 1660-1900* (Trowbridge, Wiltshire, 1991).
Bazerman, C, *Shaping Written Knowledge* (Madison, Wisconsin, 1988).
Bennett, J, A, 'A Viol of Water or a Wedge of Glass', in Gooding, D; Pinch, T; Schaffer, S, (eds.) *The uses of experiment* (Cambridge, 1989).
Bennion, E, *Antique Medical Instruments* (London, 1980).
Berman, A, *Vacuum Engineering Calculations, Formulas, and Solved Exercises* (London, 1992).
Bijker, W, *Of Bicycles, Bakelites and Bulbs* (Cambridge, Mass, 1995).
Blakemore, C. and Jennett, S, *The Oxford Companion to the Body* (Oxford, 2001).
Brachner, A, *Geschichte der Vakuumpumpen* (Deutches Museum, München, Undated).
Brayne, M, *The Greatest Storm* (Sutton Publishing, 2003).

Brockbank, W, *Ancient Therapeutic Arts* (London, 1954).
Brown, J, *Mathematical Instrument-Makers in the Grocers' Company 1688-1800* (London, 1979).
Brundtland, T, *The laboratory work of professor Kristian Birkeland* ISBN 82-90487-90-8 (University of Tromsø,Tromsø, 1997).
Bud, R, *Manifesting Medicine. Bodies and Machines* (Amsterdam, 1999).
– and Warner, D, *Instruments of Science, an Historical Encyclopedia* (London, 1998).
Burnett, J. A. *History of the cost of living* (1969). Reprint: (Aldershot, Hampshire 1993), 131.
Calvert, H. R, *Scientific Trade cards*, in the Science Museum, (London, 1971).
Clark, D. H. and Clark, S. P, *Newton's Tyranny* (New York, 2001).
Clark, W, Golinski, J, and Schaffer, S, *The Sciences in Enlightened Europe* (London, 1999).
Clark-Kennedy, A, *Stephen Hales, D.D, F.R.S, An Eighteenth Century Biography* (Cambridge, 1929).
Clay, R, and Court, T, *The History of the Microscope* (London, 1932).
Clercq, P. de, *At the Sign of Orintal Lamp. The Musschenbroek Workshop in Leiden, 1660-1750* (Rotterdam, 1997).
Clifton, G, and Turner, G. L'E, *Directory of British Scientific Instrument-makers, 1550-1851* (London, 1995).
Clifton, G, *Directory of British Scientific Instrument-makers 1550-1851* (London, 1995).
Cole, F, 'The History of Anatomical Injections', in Singer, C. J. (ed.), *Studies in the History and Method of Science* (Oxford, 1921).
Conant, J. B, 'Robert Boyle's Experiments in Pneumatics', in Conant, J. B. (ed.), *Harvard Case Histories in Experimental Science* (2 vols. Cambridge, Ma, 1957).
Cope, Z, *William Cheselden (1688-1752)* (Edinburgh, 1953).
Crom, T. R, *Trade Catalogs 1542-1842* (Melrose, Florida, 1982).
Cudworth, W, *Life and Correspondence of Abraham Sharp* (London, 1889).
D. H. D. Roller, 'Introduction' to Physico-Mechanical Experiments', *The sources of Science* (H. Woolf, ed), no. 90 (London, 1970), xvii.
D'Oench, E, *The conversation Piece: Arthur Devis & His Contemporaries* (New Haven, 1980).
Daintith J. and D. Gjertsen, D, (eds.), *A Dictionary of Scientists* (Oxford, 1999).
Daniels S, *Joseph Wright* (London, 1998).
Daston, L. and Park, K., *Wonders and the Order of Nature, 1150-1750* (New York, 1998).
Daumas, M, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers* (London, 1989).
Debus, A, *Man and Nature in the Renaissance* (Cambridge, 1995).
Dibner, B, *Early Electrical Machines* (Norwalk, Connecticut, 1957).
Egerton, J. *Wright of Derby* (London, 1990).
Ferguson, E. S, *Engineering and the mind's eye* (London, 1992) 77-82.
Frängsmyr, T, *Science in Sweden. The Royal Swedish Academy of Sciences 1739-1989* (Canton, MA, USA, 1989).
– (ed.), *Salomon's House Revisited: The Organization and Institutionalization of Science* (Canton, MA, 1990).
– ; Heilbron, J; and Rider, R, *The Quantifying Spirit in the 18th Century* (Berkely; Los Angeles; Oxford, 1990).
French, R, *Dissection and Vivisection in the European Renaissance* (Ashgate, 1999).
Gillispie, C, (ed.), *Dictionary of scientific biography* (16 vols, New York, 1981).

Goldwater, L, *Mercury. A History of Quicksilver* (New York, 1972).
Golinski, J, *Making Natural Knowledge* (Cambridge, 1998).
Gooding, D, *Experiment and the Making of Meaning* (London, 1990).
– ; Pinch, T; Schaffer, S, (eds.) *The uses of experiment* (Cambridge, 1989).
Gowing, R, *Roger Cotes – Natural Philosopher* (Cambridge, 1983).
Grant, E, *Physical Science in the Middle Ages* (Cambridge, 1993).
Guerlac, H, 'Sir Isaac and the Ingenious Mr. Hauksbee', in Cohen, B. and Taton, R. (eds.), *Melanges Alexander Koyre: L'aventure De La Science* (Paris, 1964).
– *Essays and Papers in the History of Modern Science* (Baltimore and London, 1977).
– 'F. Hauksbee', in Gillispie, C, (ed.), *Dictionary of scientific biography* (16 vols, New York, 1981).
Hackmann, W, *Electricity from Glass* (Alphen and der Rijn; The Netherlands, 1978).
– 'Scientific Instruments: Models of Brass and Aid to Discovery', in Gooding, D; Pinch, T; Schaffer, S, (eds.) *The uses of experiment* (Cambridge, 1989).
– Cataloge of Pneumatical, Magnetical and Electrical Instruments (Museo di Storia della Scienza, Florence, 1995).
Hankins, T, *Science and the Enlightenment* (Cambridge, 1985).
– and Silvermann, R, *Instruments and the Imagination* (Princeton, 1999).
Hartley, H, *The Royal Society : Its Origins and Founders* (London, 1960).
Harvey, E, *A History of Luminescence* (Philadelphia, 1957).
Heal, A, *London Tradesmen's Cards of the XVIII Century* (New York, 1968).
– *Sign Boards of Old London Shops* (London, 1957).
Heering, P, 'The Replication of the Torsion Balance Experiment. The Inverse Square Law and Its Refutation By Early18th-Century German Scientists', in Blondel, C. and Dörries, M. (ed.), in *Restaging Coulomb* (Firenze, 1994).
– ; Riess, F; and Sichau, C, *Im Labor Der Physikgeschichte* (Oldenburg, 2000).
Heilbron J, *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics* (Berkeley, 1979).
– *Physics at The Royal Society during Newton's Presidency* (Los Angeles, 1983).
– 'Some uses for catalogues of old scientific instruments', in Anderson, R. G. W, (ed.), *Making Instruments Count* (Cambridge, 1993).
– *The Oxford Companion to the History of Modern Science* (Oxford, 2003).
Helden Anne C. van, 'Air-pumps' in R. Bud and D. Warner (eds.), *Instruments of Science, an Historical Encyclopedia* (London, 1998).
– 'Air-pump and Vacuum-pump', in. J. Heilbron (ed.), *Oxford Companion to the History of Modern Science* (Oxford, 2003).
Helden, Albert van, 'The Birth of the Modern Scientific Instrument, 1550-1700', in Burke, J. J. G. (ed.), *The Uses of Science in the Age of Newton* (Los Angeles, 1983).
Hodgkin, T, *A Catalogue of the Preparations in the Anatomical Museum of Guy's Hospital* (London, 1829).
Home, R. W, 'Francis Hauksbee's theory of electricity', in Truesdell, C (ed.) *Archive for History of Exact Sciences* 4.10 (Berlin, 1967).
Hunter, M, *The Royal Society and its Fellows, 1660-1700* (Oxford, 1994).
Jones, W, *Ministering to Minds Diseased, A history of Psychiatric Treatment,* (London, 1983).
Langmuir E, *Visitor's Guide* (The National Gallery, London, 1997).
Latour, B, *Laboratory Life* (Princeton, 1986).
Leppin & Masche, *Physikalischer Apparate (*Elberfelt, Pfingsten, 1896).
Lienhard, J, *The Engines of Our Ingenuity* (Oxford, 2000).

Lindquist, S, 'A Wagnerian Theme in the History of Science' in T. Frängsmyr (ed.), *Salomom's House revisited* (Canton, MA, 1990).
Loudon, I, *Western Medicine, an Illustrated History* (Oxford, 1997).
MacGregor, A, *Sir Hans Sloane, Collector, Scientist, Antiquary, Founding Father of the British Museum* (London, 1994).
Maddison, R, *The life of the Honourable Robert Boyle* (London. 1969).
Matthew, H; Harrison, B; Goldman, L (eds.) *Oxford Dictionary of National Biographies* (Oxford, 2004).
Middleton W.E.K, *The History of the Barometer* (Baltimore, 1964).
– *The Experimenters* (Baltimore, 1971).
Millburn, J. R, *Benjamin Martin, Author, Instrument-Maker, and "Country Showman"* (Leiden, 1976).
– *Retailer of the Sciences* (London, 1986).
Morton, A. Q. and Wess, J. A, *Public & Private Science, The King George III Collection* (Oxford, 1993).
Morton, A. G, *History of Botanical Science* (London, 1981).
Nichols, J, *Illustrations of the Literary History of the eighteenth century* (8 vols, London, 1817).
Nickles, T, 'Justification and experiment', in Gooding, D; Pinch, T; Schaffer, S, (eds.) *The uses of experiment* (Cambridge, 1989).
Nicolson, B, *Joseph Wright of Derby* (London, 1968), 113)
O'Brien, P; Keene, D; Hart, M.'t; Wee, H, (eds.), *Urban Achievement in Early Modern Europe* (Cambridge, 2001).
Peachey, G. C, *William Bromfield 1713-1792* (London, 1917).
– *A Memoir of William & John Hunter* (Plymouth, 1924).
Pinch, T, *Confronting Nature* (Dordrecht, 1986).
Polanyi, M, *Personal Knowledge* (London,1962).
– *The Tacit Dimention* (London,1966).
Porter, R, (ed.), *The Cambridge Illustrated History of Medicine* (Cambridge, 1996).
– *The Scientific Revolution in National Context* (Cambridge, 1992).
– *The Enlightenment* (London, 2000).
– and Mikulas, T, *The Enlightenment in National Context* (Cambridge,1981).
Pumfrey, S, 'Hauksbee, Francis' in L. Goldman (ed.) *Oxford Dictionary of National Biographies* (Oxford, 2004).
Purver, M, *The Royal Society : Concept and Creation* (London, 1967).
Roberts, K. B, *The Fabric of the Body, European Traditions of Anatomical Illustration* (Oxford, 1992).
Roller, D. and Roller, D. H. D, 'The Development of the Concept of Electric Charge. Part 3. Francis Hauksbee', in Conant, J. B, (ed.), *Harvard Case Histories in Experimental Science* (Cambridge, Massachusetts, 1957).
Roth, A, *Vacuum Technology* (Amsterdam, 1976).
Rupke, N. A, *Vivisection in Historical Perspective* (London, 1987).
Russell, K. F, *British Anatomy 1525-1800* (Winchester, 1987).
Salaman, R. A, *Dictionary of Woodworking Tools C.1700-1970 and Tools of Allied Trades* (London, 1989).
Schaffer, S, 'Glass Works: Newton's Prisms and the Uses of Experiment', in Gooding, D; Pinch, T; Schaffer, S, (eds.) *The uses of experiment* (Cambridge, 1989).
Shapin, S, *A Social History of Truth* (Chicago, 1994).
– and Schaffer, S, *Leviathan and the Air-pump* (Princeton, 1985).

Stewart, L, *The Rise of Public Science* (Cambridge, 1992)
– 'Philosophers in the counting-houses: commerce, coffee-houses and experiments in early modern London', in P. O/Brien; D. Keene; M.'t Hart; H. Wee (eds.), *Urban Achievement in Early Modern Europe* (Cambridge, 2001), 326-45.
Taylor, E. G. R, *The Mathematical Practitioner of Tudor & Stuart England* (Cambridge, 1954).
– *The Mathematical Practitioner of Hanoverian England 1714-1840* (Cambridge, 1966).
Teacher, J, *Catalogue of Anatomical and Pathological Preparations* (Glasgow, 1900).
The Harris Museum and Art gallery, *Polite Society by Arthur Devis*. Exhibition catalogue. (Preston, 1983), 9-10; 22; 43-4.
Thompson, C. J. S, *Guide to the Surgical Instruments and Objects in the Historical Series With Their History and Development* (London, 1929).
– *Love, Marriage and Romance in Old London* (London, 1936).
– *The History and Evolution of Surgical Instruments* (New York, 1942).
Turner, A, *Early Scientific Instruments: Europe, 1400-1800* (London, 1987).
Turner, G. L'E, *Scientific Instruments and Experimental Philosophy 1550-1850* (Aldershot, 1990).
– *Scientific Instruments, 1500-1900. An Introduction* (London, 1998).
Walker, P, (ed.), *Chambers Science and Technology Dictionary* (Edinburgh, 1992).
Westfall, R. S, *Never At Rest, a Biography of Isaac Newton* (Cambridge, 1998).
– *The Construction of Modern Science. Mechanisms and Mechanics* (Cambridge, 1990).
Yeo, R, *Encyclopaedic Visions, Scientific Dictionaries and Enlightenment Culture* (Cambridge, 2001).
Zubov, V. P, *Leonardo Da Vinci* (Cambridge, Mass, 1968).

### 3.2 Articles

Andrade, E, 'A Lecture With Experiments On Various Subjects', *Journal of Scientific Instruments*, vol. IV (Feb. 1927), 130–7.
Brundtland, T, 'A Description of the Vacuum Chamber for the Blaaman Plasma Experiment', *Vacuum* (Pergamon Press), vol. 43 no. 3 (March 1992). 185-7.
– 'Public Lectures on Natural Philosophy in early 18th century London', in: Kunnskap og kunnskapsformidling på 1700-tallet [Knowledge and dissemination of knowledge in the eighteenth century]. ISBN 82-997000-0-0 (Oslo, 2004).
– 'Blåmann, a description of the vacuum system' [Blåmann – beskrivelse av vakuuksystemet] *Journal of the Swedish Vacuum Council* (1995).
Bryden, D. J, 'Evidence from Advertising for Mathematical Instrument Making in London, 1556-1714', *Annals of Science*, vol. 49 (1992), 301–36.
Chipman, R. A, 'An Unpublished Letter of Stephen Gray On Electrical Experiments 1707-1708', *Isis*, vol. 45 (May, 1954).
Clark, D. H. and Murdin, L, 'The Enigma of Stephen Gray, Astronomer and Scientist', *Vistas in Astronomy*, 23, (1979), 351–404.
Clark-Kennedy, A. E, 'Stephen Hales, 1677-1761. Physiologist and Botanist', *The Lancet*, June 18th (1927), 19.
Collins, H. M. and Kusch, M, 'Automating Air-pumps: An Empirical and Conceptual Analysis', *Technology and Culture*, 36 (1995), 802–29.
Corson, D. W, 'Pierre Poliniere, Francis Hauksbee, and Electroluminescence: A Case of Simultaneous Discovery', *ISIS*, 59 (1968), 402–13.

Crawforth, M. A, 'Evidence from Trade Cards for the Scientific Instruments Industry', *Annals of Science*, 42 (1985), 453–554.
– 'Instrument-Makers in the London Guilds', *Annals of Science*, 44 (1987), 354.
Field, J. V, 'What Is Scientific About a Scientific Instrument?', *Nuncius*, 3 (1988), 3–26.
Freudenthal, G, 'Electricity Between Chemistry and Physics: The Simultaneous Itineraries of Francis Hauksbee, Samuel Wall, and Pierre Polinière', *Historical Studies in the Physical Sciences*, Vol. 11 (1981), 203-29.
Helden, A. C. van, 'The Age of the Air-Pump', *Tractrix*, vol. 3 (1991), 149-172.
– 'Theory and Practice in Air-Pump Construction', *Annals of Science*, vol. 51 (1994), 477–95.
– 'Stabilised forms of Philosophical Instruments', Proceedings from XVIII International Scientific Instrument Symposium, Moscow 1999 (Moscow, 2002), 67-79.
Helden, Albert van, and Hankins, T. L, 'Introduction: Instruments in the History of Science', *Osiris*, 9 (1994), 1–6.
Lawrence, C, 'Alexander Monro Primus and the Edinburg Manner of Anatomy', *Bulletin of the History of Medicine*, 62, No 2 (1988), 193–214.
Pumfrey, S, 'Who Did the Work? Experimental Philosophers and Public Demonstrators in Augustan England', *British Journal of the History of Science*, 28 (1995), 131–56.
Roberts L, 'Science becomes electric', *Isis* vol. 90, No 4 (Dec. 1999), 684.
Roller, D. and Roller, D. H. D, 'Francis Hauksbee', *Scientific American*, vol. 189 (1953), 65-69.
Senior, J. E, 'Hauksbee's Prototypical Electrostatic Generator', *Medical Instrumentation*, 17 (1983), 126–7.
Shapin, S, 'Pump and Circumstances: Robert Boyle's Literary Technology', *Social Studies of Science*, 14 (1984), 481–520.
– 'The House of Experiments in Seventeenth-Century England', *ISIS*, 79 (1988), 373–404.
Sibum, O. H, 'Reworking the Mechanical Value of Heat: Instruments of Precision and Gestures of Accuracy in Early Victorian England', *Studies in History and Philosophy of Science*, 26 (1995), 73–106.
Stroup, A., 'Christiaan Huygens & the Development of the Air-pump', *Janus*, vol. LXVIII (1981), 129–58.
Turner, G. L'E, 'The Government and the English Optical Glass Industry, 1650-1850', *Annals of Science*, 57, (2000), 399–414.
Warner, D, 'What Is A Scientific Instrument, When Did It Become One, and Why?', *British Journal of the History of Science*, 23 (1990), 83–93.
Wess, J. A, 'Lecture Demonstrations and the Real World: The Case of the Cart Wheels', *British Journal of the History of Science*, 29 (1995), 79–90.
Wilson G, 'On the Early History of the Air-pump in England', *The Edinburgh New Philosophical Journal*, vol. XLVI (1849), 330–54.