

DEVELOPMENT OF A NOVEL MASS FLOW MEASUREMENT DEVICE FOR HIGH SPEED INLET TESTING

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ABSTRACT

A novel mass capture device for testing high speed inlets in short duration facilities has been developed. The device improves upon the accuracy and sensitivity of current methodologies by separating the mass flow measurement from the back-pressure inducing capability. It also has sufficient temporal response for reliable application to short duration test facilities. This paper describes the principles of the operation and the design process of the mass capture device. Calibration was performed using a steady flow bench top test using an orifice mass flow meter. The device's suitability for use in transient hypersonic flow facilities was validated in the Oxford High Density Tunnel by connection to a simple Pitot inlet that achieves full mass capture.

Index Terms— Supersonic, Inlet, Mass Capture, Scramjet

1. INTRODUCTION

Air breathing vehicles that fly much faster than the speed of sound, such as ramjets and scramjets, rely solely upon the inlet geometry to perform compression of the incoming freestream air. The amount of mass captured by the inlet is a critical parameter that affects the overall performance and efficiency of the engine. Van Wie [1] predicted that to maintain 1 % accuracy in specific impulse over the range Mach 5 to 10, the accuracy in mass capture must be in the range 1 to 3 %. The ability of an inlet to self-start is also desirable due to the operational simplicity this affords. Both the self-starting and mass capture characteristics are highly sensitive to the flow fields produced by any given inlet geometry, so it is vital that numerical predictions of performance be validated against accurate experimental measurement of these inlet characteristics.

With the prohibitive cost of flight testing, inlet characterisation is typically performed in high speed wind tunnels. Tests are conducted at conditions that match the flight Mach and Reynolds numbers, thereby ensuring similarity of the flow field. Mechanically increasing the back-pressure until the inlet unstarts permits quantification of the effects of combustor

operating pressure on the mass capture and the self-starting capability of the inlet.

Shown schematically in Figure 1, a traditional method for high speed inlet mass flow measurement uses a translating cone to restrict the flow exiting from a dump isolator. The mass flow measurement is taken where the gas chokes when passing the cone. This type of device allows some modulation in the annular restriction of the back-pressure to the inlet. Typically, baffle plates and flow straighteners are used to ensure that the measurements of total pressure and total temperature are representative of the stagnated flow. Devices of this sort have been successfully incorporated in testing in the NASA blowdown tunnels by Smart [2] and several tests in the H2k facility [3–6]. In the work described in Hohn and Gülhan [4], an accuracy of $\pm 3\%$ for the mass flow rate was achieved.

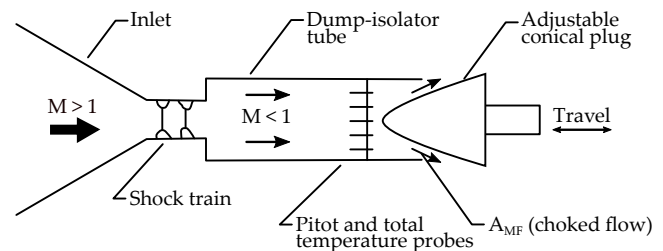


Fig. 1. Schematic of traditional method for inlet mass capture measurement device.

The difficulties with such a device are (1) uncertainties due to the sensitivity and non-linearity of the back-pressure to the position of the rear cone, (2) large response times of the device, specifically the temperature measurement and fill times when tested in short duration facilities, (3) coupling of the back-pressure with the mass flow rate, and (4) the use of non-ISO-standard measurement geometry decreases accuracy over wide ranges of Reynolds numbers.

This paper describes a novel mass capture device where the mass flow measurement and back-pressure functions are separated in order to provide improvements over traditional de-

signs. Section 2.1 describes the principles of operation, design and instrumentation. Steady-state calibration results, in which the device was compared against an ISO 15377 orifice plate, are also presented in Section 2.1, providing accurate characterisation of the device. Section 3 describes the performance for high speed, short duration tests by presenting results of a 100 % capture Pitot inlet that was tested in the Oxford High Density Tunnel (HDT). As a result, the ability of this novel device to accurately characterise the mass capture and back-pressure capability of hypersonic inlets has been demonstrated. The paper finishes in Section 4 with some conclusions and an outlook to future work.

2. NOVEL MASS CAPTURE DEVICE

2.1. Principles of Operation

A new back-pressure/mass flow measurement device was developed which separates the measurement of mass flow from the back-pressure capability. Shown schematically in Figure 2, the device consists of a dump-isolator downstream of the inlet and a secondary isolator downstream of a variable area restrictor. Through careful selection of the area ratios for the combined device-inlet system, which account for the dynamic head losses, the variable area restrictor sets the back-pressure to the inlet while the subsequent subsonic flow downstream is re-accelerated through a fixed area, choked nozzle, providing accurate measurement of the mass flow.

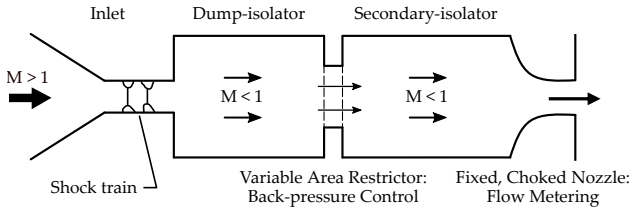


Fig. 2. Schematic of inlet mass capture measurement device with separated back-pressure and mass capture function.

The variable area restrictor consists of two perforated, circular plates that rotate relative to each other in a controlled manner (Figure 3). The upstream plate is held fixed while the downstream plate is rotated by a stepper motor, housed outside the main flow path, via a spur gear mechanism. Since the plate is driven perpendicular to the flow, the motor experiences less load than the translating cone device as shown in Figure 1. Rapid, controlled changes in restriction area are possible, potentially allowing the mass capture characteristics during a complete start-unstart event of an inlet to be recorded transiently in a single experiment. Furthermore, the hole patterns may be specified so as to optimise the back-pressure profile relative to the actuation.

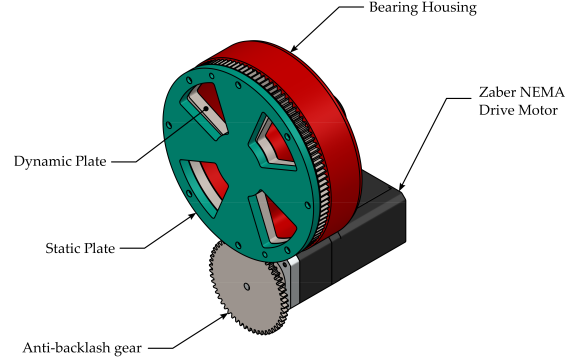


Fig. 3. Isometric view of variable area restrictor and drive motor.

2.2. Design and Instrumentation

The mass capture device (MCD) is shown in Figure 4 together with the Pitot inlet used for validation experiments. Both were machined from 7075-T6 billet aluminium. The MCD features a 120 mm diameter bore that is 410 mm in length and has a maximum pressure rating of 35 bar. The flow exits through a $d_{nt} = 40.00(4)$ mm diameter venturi nozzle that has an internal profile in accordance with ISO 9300:2005(E). The variable area restrictor was located 204 mm downstream of the entrance to the MCD. In the current configuration, both the static and dynamic circular plates featured four circumferential slots as shown in Figure 3. The dynamic plate was manufactured from a Reliance Precision Ltd spur gear (PNo. S1.25S 110A-0818F) and was driven using a Zaber NEMA stepper motor (PNo. X-NMS17CWE01-KX13CG) via a Reliance Precision Anti-backlash gear (PNo. AP125S1B5F35A-35).

The MCD was instrumented with three Kulite® XT-190(S)M absolute pressure transducers. Labelled P_{MC2} , P_{MC3} and P_{MC4} in Figure 4, each had a range of 0 to 3500 kPa and uncertainty ± 0.1 % FS. P_{MC2} and P_{MC3} were located upstream and downstream of the restrictor (respectively) while P_{MC4} was located at the exit of the MCD and, in combination with P_{MC3} on the backward facing step, was used to monitor the pressure ratio across the venturi nozzle. A fourth measurement location, P_{MC1} , was located on the backwards facing step at the entrance to the MCD but was not instrumented in this work.

The temperature upstream of the venturi, T_{MC2} , was measured using a 0.005 inch diameter Omega K-Type thermocouple (PNo. TT-K-36-SLE) housed in a bespoke mounting body. This mounting body positioned the thermocouple bead approximately 1 mm proud of the internal surface. The uncertainty of the thermocouple was 1.1 K.

To enable validation experiments in the Oxford HDT, a Pitot inlet that achieves a 100 % capture ratio of the freestream was designed. It featured an inlet diameter of 36.70(5) mm and an exit diameter of 31.50(5) mm, giving a contraction ratio of 1.17. This small contraction ratio was chosen to ensure that

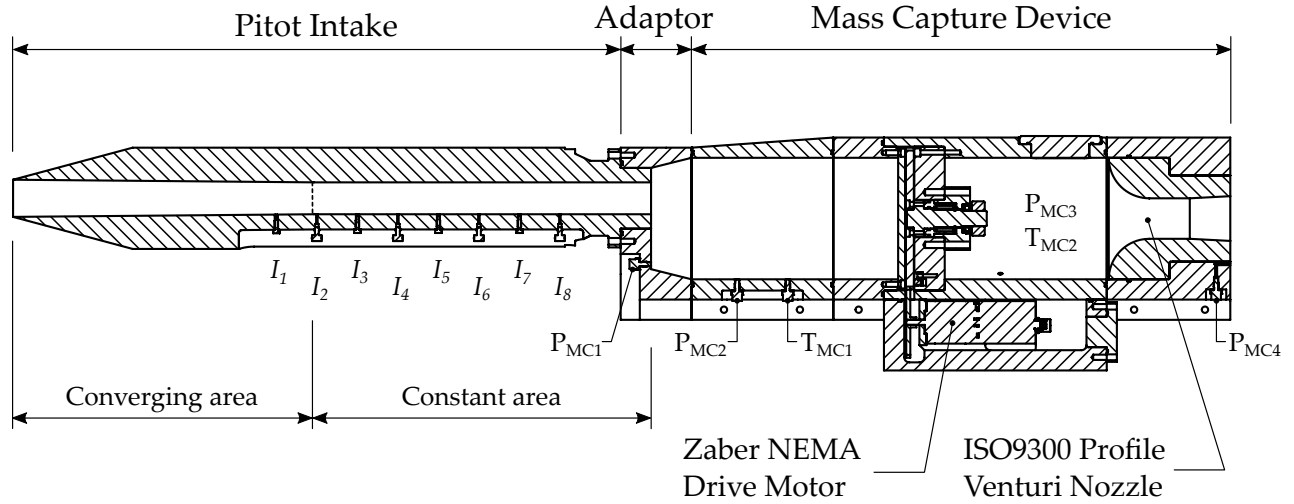


Fig. 4. Cross-section through the mid-plane of the Mass Capture Device. For clarity, the associated mounting hardware is not shown.

the Pitot inlet started. The length of the contracting portion of the inlet was 297 mm and the overall inlet length was 630 mm. The inlet was instrumented with a combination of Kulite® XTL-140M absolute pressure transducers with ranges 0 to 70 kPa (I_1) and 0 to 150 kPa (I_3 , I_5 , I_7) and Honeywell HSC absolute pressure transducers with ranges 0 to 15 psi (I_2 , I_4) and 0 to 30 psi (I_6 , I_8). The associated uncertainties are taken to be $\pm 0.1\%$ FS and $\pm 1\%$ FS for the Kulite® and Honeywell sensors respectively.

2.3. Benchtop Calibration Rig

A bench top rig was developed to calibrate the MCD under steady flow conditions and to allow examination of the response time of the system. Shown in Figure 5, the rig was designed in accordance with BS EN ISO 5167-2:2003 and featured a 61.2 mm diameter, squared-edged orifice plate (Rototherm PNo. FOP-SM1-100M-01700x0003/125x32/N0.0-562291). The calibration rig was connected to a large reservoir of 400 psi air via a 2 inch IMI Norgren pilot regulator (PNo. R18-B00-RNXD) which was used to control the supply pressure of the incoming air.

The exit of the regulator was connected to a 2 inch 90° elbow and a 1100 mm length of 2 inch pipe work. The pipe work was expanded to 4 inch using a Victaulic No. 50 concentric expander/reducer. A Zanker flow conditioner, designed in accordance with BS EN ISO 5167-2, was installed a distance 1500 mm downstream of the expansion; this distance was 15D relative to the nominal internal diameter of the pipe work. The orifice plate was located a further 1500 mm downstream of the Zanker plate. The MCD was connected 1500 mm downstream of the orifice plate via a bespoke flange which increased from 102 to 120 mm diameter via a 10.5° half-angle expansion. At the exit of the MCD the air flow was exhausted

to atmosphere through four ASCOnumatics high flow mufflers (PNo. SE200HB).

The internal diameter of the pipe work upstream of the orifice plate was measured to be 101.97 mm. This value was an average of 20 micrometer measurements, with four measurements taken at cross-sections 25 mm, 50 mm, 100 mm, 125 mm and 150 mm upstream of the orifice. The diameter ratio of the orifice plate was therefore $\beta = 0.60$.

The differential pressure across the orifice, ΔP , was measured using an Omega PX419-100DDU5V differential pressure sensor with range 0 to 100 psid and uncertainty $\pm 0.08\%$ FS BSL. The static pressure upstream of the orifice, P_1 , was measured using an Omega PX419-100A10V-EH absolute pressure sensor with range 0 to 100 psi and uncertainty $\pm 0.05\%$ FS BSL. The static pressure sensor was connected to the same upstream pressure taps as the differential pressure sensor.

The static temperature upstream of the orifice was not directly measured but was calculated from the downstream static temperature, T_3 , assuming an isenthalpic expansion (as per the standard). The downstream temperature was measured at a location 1000 mm from the orifice plate using a 0.005 inch diameter Omega K-Type thermocouple (PNo. TT-K-36-SLE). This thermocouple was mounted using 1 mm diameter Scanivalve tube glued into the pipe side wall. The thermocouple bead was ≈ 5 mm from the pipe centreline. Finally, the downstream wall static pressure, P_3 , was measured in the same cross-section as T_3 using a Sensortech CTE9010GP0 gauge-pressure sensor with range 0 to 10 barg and uncertainty $\pm 0.1\%$ FS.

The data acquisition system for the calibration rig consisted of a National Instruments cDAQ-9184 chassis fitted with an NI-9220 analogue voltage input card and the combination of an NI-9214 thermocouple module with TB-9214 isothermal terminal block. Kulite® pressure sensors installed in the MCD were amplified using Fylde FE-H379-TA amplifiers. The calibration

rig and MCD pressure signals were recorded with a sampling rate of 1000 Hz while thermocouple signals were recorded using “high-resolution mode” with a sampling rate of 30 Hz.

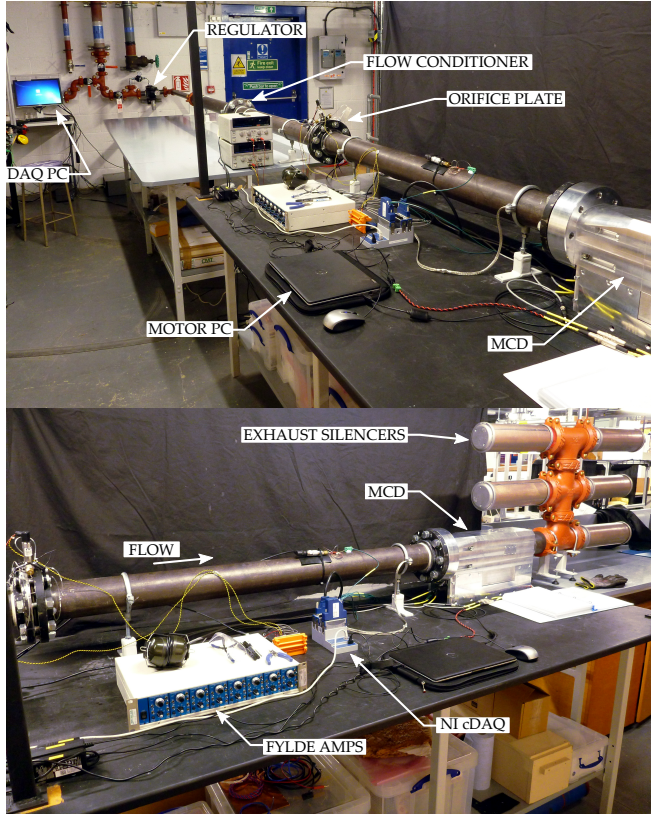


Fig. 5. BS EN ISO 5167-2 Mass-flow Calibration Rig

2.4. Benchtop Calibration Results

Sample transient results obtained from the calibration rig for calibration H are presented in Figure 6. In this calibration, the feed pressure was increased in increments of approximately 100 kPa by (manually) adjusting the upstream pressure regulator (Figure 5). At each increment, the feed pressure was held constant for approximately 10 s to allow the system to stabilise. Each steady plateau in Figure 6 represents one usable calibration interval.

BS EN ISO 5167-2 for the orifice plate and ISO 9300 for the venturi each give criteria on valid ranges for the pressure ratio across each device and the corresponding Reynolds number.¹ In Figure 6, the pressure ratios of the devices are plotted only for their individual ranges of validity; Reynolds numbers and mass flow rates are plotted for the period where the Reynolds number is additionally valid. Finally, the calculated discharge coefficient of the venturi is plotted only where mass flow of both devices is valid.

¹For the orifice, the Reynolds number is calculated with respect to the upstream flow, $Re_D = 4q_o/(\pi\mu_1 D)$; for the venturi, it is calculated with respect to the throat, $Re_{nt} = 4q_v/(\pi\mu_{MC3} d_{nt})$.

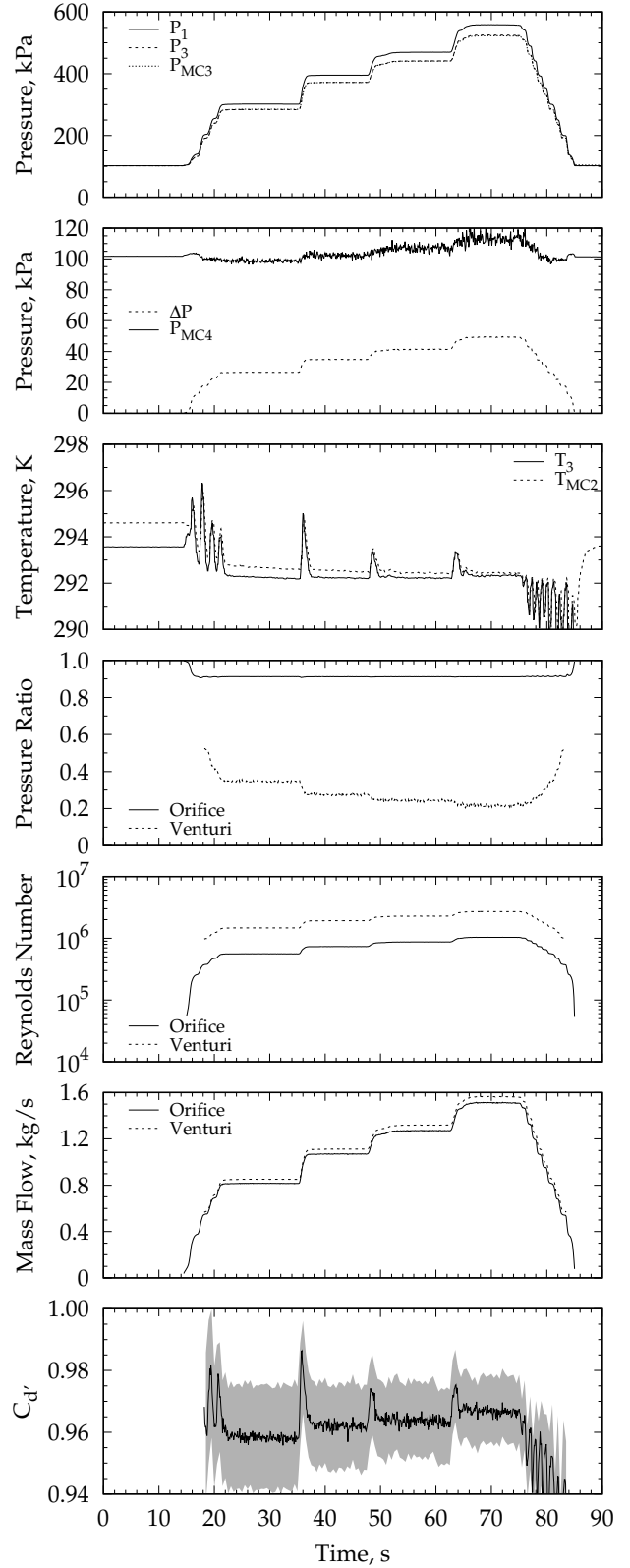


Fig. 6. Time histories recorded for calibration H. All signals have been filtered using a 100 ms moving average filter. The shaded region C_d indicates the experimental uncertainty.

As per BS EN ISO 5167-2, the mass flow through the orifice was calculated using

$$q_o = \frac{C}{\sqrt{1-\beta^4}} \epsilon \frac{\pi}{4} d^2 \sqrt{2\rho_1 \Delta P} \quad (1)$$

where $C = f(\beta, Re_D)$ is the orifice discharge coefficient, ρ_1 is the static density upstream of the orifice plate, ΔP is the pressure drop across the orifice and ϵ is the expansibility factor given by

$$\epsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8) \left[1 - \left(\frac{P_1 - \Delta P}{P_1} \right)^{1/\gamma} \right] \quad (2)$$

The upstream density ρ_1 was not measured directly in this work but was inferred from the far-downstream temperature and pressure using

$$\rho_1 = \frac{P_1}{R(T_3 + \mu_{JT}(P_1 - P_3))} \quad (3)$$

where $\mu_{JT} = 0.22 \times 10^{-5}$ K/Pa is the Joule-Thomson coefficient for air.

For the venturi in the MCD, the mass flow was calculated in accordance with ISO 9300 using

$$q'_v = \frac{A_{nt} C_* P_{0,MC3}}{\sqrt{RT_{0,MC2}}} \quad (4)$$

where A_{nt} is the throat area of the venturi, and C_* is the critical flow function –

$$C_* = \sum_i a_i \left(\frac{P_{0,MC3}}{P_c} \right)^{b_i} \left(\frac{T_{0,MC2}}{T_c} \right)^{c_i} \quad (5)$$

where $P_c = 3.786$ MPa and $T_c = 132.5306$ K are the critical pressure and temperature of air, and $P_{0,MC3}$ and $T_{0,MC2}$ are the total pressure and temperature upstream of the venturi which are related to the measured P_{MC3} and T_{MC2} via isentropic flow equations.

Finally, the calibrated discharge coefficient for the venturi was calculated using

$$C_{d'} = \frac{q_o}{q'_v} \quad (6)$$

The uncertainty in the average discharge coefficient from a period in each calibration run was calculated using

$$\begin{aligned} X_{C_{d'}}^2 &= X_C^2 + X_\epsilon^2 + \left(\frac{2\beta^4}{1-\beta^4} \right)^2 X_D^2 \\ &+ \left(\frac{2}{1-\beta^4} \right)^2 X_d^2 + \frac{1}{4} X_{\Delta P}^2 + \frac{1}{4} X_{\rho_1}^2 \\ &+ 2X_{d_{nt}}^2 + X_{C_*}^2 + X_{P_{MC3}}^2 + \frac{1}{4} X_{T_{MC2}}^2 \end{aligned} \quad (7)$$

where $X_a = \frac{\delta a}{a}$ is the relative uncertainty in variable a . The uncertainty in the expansibility factor and upstream density are respectively given by Equations (8) and (9) as follows –

$$X_\epsilon^2 = \left(3.5 \frac{\Delta P}{\gamma P_1} \right)^2 \quad (8)$$

$$X_{\rho_1}^2 = \frac{(T_3 - \mu_{JT} P_3)^2 X_{P_1}^2 + (\delta T_3)^2 + (\mu_{JT} \delta P_3)^2}{(T_3 + \mu_{JT}(P_1 - P_3))^2} \quad (9)$$

Figure 7 plots the averaged discharge coefficient from each calibration interval against the throat Reynolds number, Re_{nt} of the venturi. For clarity, experimental uncertainties are provided for selected calibrations only. Calibrations A, B, C, D and H were each conducted with the restrictor fully open. The flow through area was equivalent to a diameter of 78.7 mm. Calibrations E, F and G were conducted with the restrictor partially closed, with flow-through areas equivalent to diameters of 50 mm, 40 mm and 30 mm, respectively.

The overall average discharge coefficient across all calibrations was $\bar{C}_{d'} = 0.942(17)$ which is indicated in Figure 7 by a horizontal dashed line. Its uncertainty is indicated by the shaded region and accounts for correlated uncertainties between each calibration used in determination of the average.

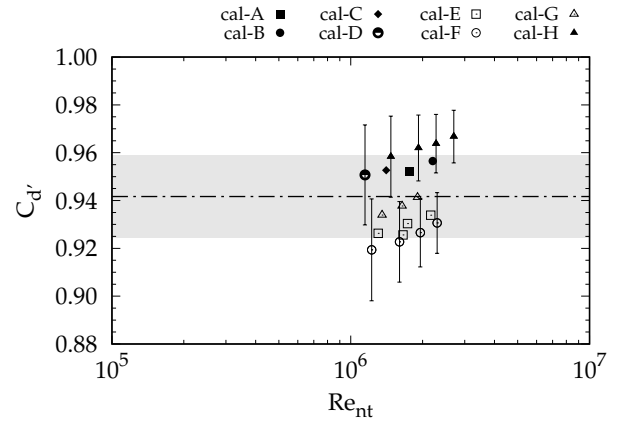


Fig. 7. Discharge coefficient variation with venturi-throat Reynolds number. For clarity experimental uncertainties are provided only for selected calibrations.

The uncertainty in $\bar{C}_{d'}$ corresponds to 1.8% which was considered acceptable for this initial investigatory work. This uncertainty was dominated by the differential pressure ΔP and venturi static pressure P_{MC3} measurements. Changing the associated sensors would reduce the coefficient uncertainty to approximately 0.5%.

Figure 7 indicates a slight dependency of the discharge coefficient on the throat Reynolds number, with calibrations performed at higher values of Re_{nt} i.e. higher mass flow rates, having higher discharge coefficients. There also appears to be a small dependency of the discharge coefficient on the status

of the upstream restrictor, with calibrations conducted with the restrictor fully open (filled symbols) resulting in higher discharge coefficients than those conducted with the restrictor partially closed (open symbols). It is expected that these observed dependencies are related to flow non-uniformities within the MCD and the location/measurement of P_{MC3} and T_{MC2} . These sensors could not be located strictly in accordance with ISO 9300 due to size restrictions placed on the MCD by the HDT Test Section and test flow duration. For this work, the dependencies were considered sufficiently small and the overall average $\bar{C}_{dr}$ was taken to be a constant when analysing the HDT data presented in the next section. The flow non-uniformity within the MCD and its influence on the measurement of P_{MC3} and T_{MC2} will be investigated in future work.

3. EXPERIMENTAL FACILITY AND RESULTS

Experiments to validate the MCD in a short duration test facility were carried out in the University of Oxford's High Density Tunnel. This facility was originally developed by the RAE (later Qinetiq) in the United Kingdom in the 1960's. Constructed from 6-inch gun barrels, the facility was initially operated as a cold hydrogen driven shock tube and tunnel. The HDT, shown on the right in Figure 8, was acquired from Qinetiq in 2012 by the University of Oxford to widen the portfolio of hypersonic ground-test facilities within the Oxford Thermofluids Institute [7]. The facility has been installed and is now fully operational in Ludwig Tube mode. Further details of its performance during commissioning are presented in Wylie et al. [8]. This facility is capable of generating relatively long duration flows at high Reynolds number, and is suitable for both steady and unsteady aerothermodynamic testing of hypersonic configurations.



Fig. 8. Hypersonics Laboratory at the Oxford Thermofluids Institute. The T6 Stalker Tunnel is on the left and the High Density Tunnel is on the right.

3.1. Test Conditions

The test flow properties were calculated using the measured nozzle supply pressure (p_0), pitot pressure (p_p) and total tem-

perature (T_0) assuming isentropic flow of calorically perfect air with Keyes model used for the calculation of viscosity.

The facility nozzle supply pressure was measured using a Kulite XT-190(S)M absolute pressure transducer with range 0 to 3500 kPa and accuracy $\pm 0.1\%$ FS. Additionally, the experimental model was instrumented with a pitot probe and a total temperature probe. The pitot probe was instrumented with a flush-mounted Kulite XCEL-152 absolute pressure transducer with range 0 to 172 kPa and accuracy $\pm 0.1\%$ FS.

The total temperature probe was based on the work of Widodo and Buttsworth [9] and Hermann et al. [10]. It consisted of a heated aspirated thermocouple housed within a diameter 10.5 mm body and featuring a diameter 1.6 mm through hole. A K-type thermocouple with nominal diameter 0.001 inch was used and the effective length and heat transfer coefficient were characterised to be 1.39 mm and 1114 W/(m² K) respectively. Based on the work of Hermann et al. [10] the uncertainty in the total temperature measurement was taken to be ± 15 K.

A nominal condition of Mach 5, unit Reynolds number of $14 \times 10^6/\text{m}$ and total temperature of 450 K was used during testing in the HDT. The average test condition across all shots conducted for this work is reported in Table 1.

Table 1. Average Test Condition

p_0	kPa	937	± 4
p_p	kPa	60.0	± 0.5
T_0	K	449	± 15
M		4.95 ± 0.01	
p	Pa	1875	± 24
T	K	76	± 3
u_x	m/s	866	± 15
Re_u	$10^6/\text{m}$	13.6	± 0.7
ρu_x	kg/(s m ²)	74.3	± 1.4

3.2. Experimental Setup of the Pitot Inlet

The Pitot inlet and MCD assembly is shown installed in the HDT test section in Figure 9. The assembly was positioned such that leading edge of the inlet was 98.0(5) mm downstream of the nozzle exit plane and the inlet centreline was, to within measurement uncertainty, concentric with the nozzle. Previous nozzle survey data indicated that the core flow size of the Mach 5 nozzle was $\varnothing 280(5)$ mm at 137(5) mm downstream of the nozzle exit plane. The inlet capture area was therefore well positioned within the nozzle core flow.

3.3. Pitot Inlet Results

A set of shots were conducted in the HDT. For each shot, the variable area restrictor (Figure 3) within the MCD was adjusted to a fixed value throughout the duration of test flow. With the variable area restrictor fully open, the flow-through

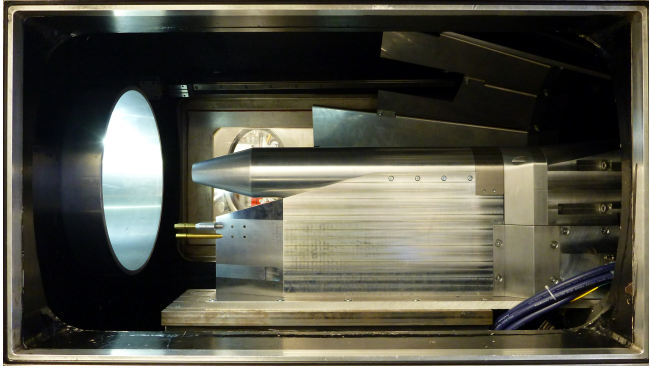


Fig. 9. Pitot inlet installed in the HDT test section with Mach 5 nozzle.

area (A_R) was equivalent to 438 % of the capture area (A_I). Six other settings of the restrictor were tested, corresponding to flow-through area ratios of 110 %, 90 %, 70 %, 50 %, 30 % and 10 %. The measured pressure distribution for each test is presented in Figure 10. Each data point represents the average over the test time of the corresponding sensor. The error bars plotted represent one standard deviation of the variation of each pressure measurement during the test time. A cross-sectional view of the inlet at the correct relative scale is also provided to aid interpretation

For the fully open test ($A_R/A_I = 438$ %, shot 716) the pressure distribution is constant and low, representing a fully started inlet. A small pressure increase occurs from I_3 (5.0 kPa) to I_8 (5.7 kPa) due to boundary layer growth. The overall static pressure ratio across the inlet ($I_8/p = 3$) is small, indicating that the freestream is only weakly compressed, as expected for this low contraction ratio design.

When the restrictor is closed, the flow field within the inlet changes such that significantly higher pressures are measured at the rear of the inlet compared with the fully open test. The start of the pressure-rise moves upstream as the flow-through area of MCD decreases. Its shape, a gradual increase in pressure, is indicative of an oblique shock-train [11] being located in the constant area section of the inlet. This shock train features greater levels of unsteadiness compared with the upstream flow, as evidenced by the larger error bars for sensors at the start of the pressure-rise. For restrictor area ratios between 30 % and 110 %, the shock train is contained completely within the inlet, with sensors I_2 to I_4 measuring identical to the fully open test.

In comparison, when the restrictor was set to 10 % of the inlet area, the pressure distribution changed significantly with every sensor elevated to an average pressure level of 54.5 kPa. This average is comparable with the expected post-normal shock pressure of 53.3 kPa calculated using the conditions reported in Table 1. Thus, for this setting of the restrictor, the inlet was unstarted with a bow-shock positioned upstream of the inlet capture area. Thus, the full range of behaviour of the inlet has been induced in a controlled manner, whilst

maintaining a fixed mass flow measurement geometry.

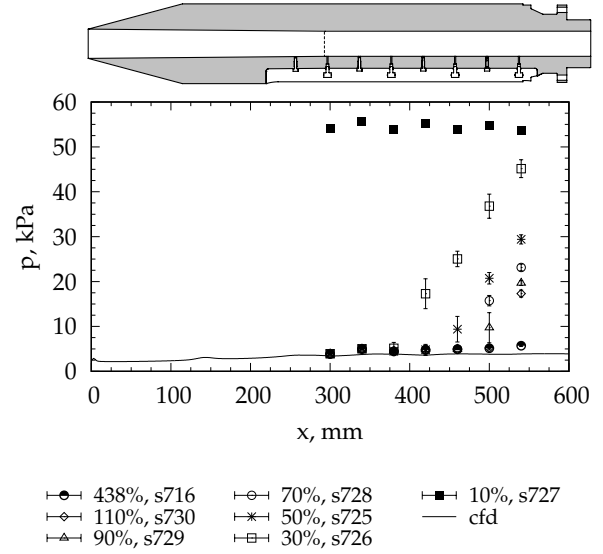


Fig. 10. Experimental static pressure distribution for different settings of the restrictor. Percentages are with respect to inlet capture area (A_I). Error bars represent one standard deviation of the variation during the test time.

Figure 11 presents the variation in inlet back-pressure (P_{MC2}) and mass flow ($q_v = q_v' C_{d'}$; cf. Equations (4) and (6)) with the restrictor area ratio. The freestream mass flow, calculated from the mass flux listed in Table 1 and inlet capture geometry, is indicated by a horizontal dashed line.

As expected, the back-pressure increases as the restrictor is closed, changing from 30 kPa with the restrictor fully open to 62 kPa with the restrictor set at 30 %. A further reduction of the restrictor flow-through area (to 10 %) causes the inlet to unstart and the back-pressure to drop. This lower back-pressure is a consequence of total pressure losses across the bow-shock sitting in front of the inlet. Although the back-pressure was lower than when the restrictor was set to 30 %, the inlet remained un-started throughout the test flow duration.

The measured mass flows presented in Figure 11 show no variation with the restrictor area ratio provided the inlet is started. This result demonstrates that the venturi mass flow measurement capability is independent of the back-pressure capability, proving the overall design of the MCD.

The average mass flow for the started inlet was measured to be 69(9) g/s, compared with 79(2) g/s calculated from the freestream mass flux and inlet capture area. This is just within the uncertainty of the MCD mass flow (approximately 13 %) which was dominated by $X_{P_{MC3}}$ and so is easily reduced in future tests by a change in pressure transducer.²

²For example, changing P_{MC3} to a transducer with range 150 kPa and uncertainty ± 0.1 % FS reduces the mass flow uncertainty to approximately 2 % (excluding corresponding improvements in $X_{C_{d'}}$)

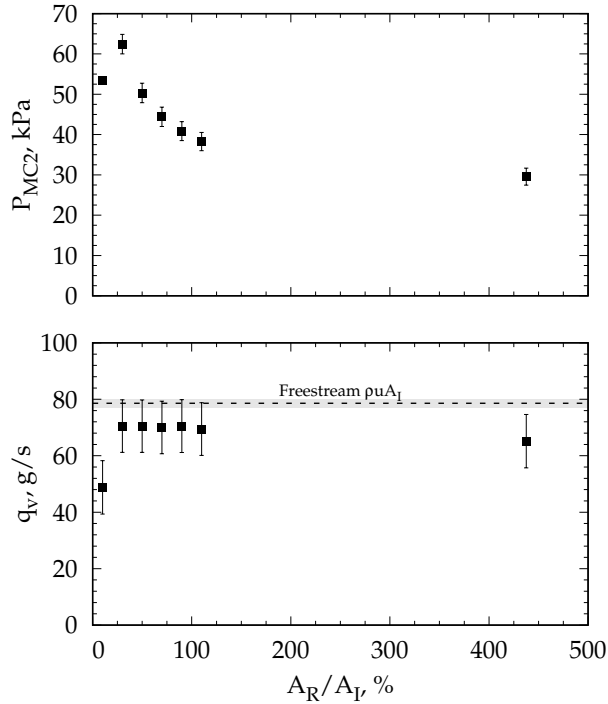


Fig. 11. Variation in back-pressure (P_{MC2}) and measured mass flow (q_v) with restrictor area. The restrictor area is given as a percentage of the capture area of the Pitot inlet. Error bars for the back-pressure represent one standard deviation of the variation during the test time; error bars for the mass flow represent the systematic experimental uncertainty.

4. CONCLUSION

This work presents the development of a novel mass capture device capable of accurate measurement of mass flow rates in short duration test facilities. The new device separates the mass flow measurement capability from the back-pressure inducing capability, improving the overall versatility. The device was calibrated against an orifice plate using a new steady-flow bench top test rig. A calibration uncertainty of 1.8% was achieved, with scope for this to be reduced to 0.5%. Short-duration validation experiments were carried out in the High Density Tunnel at a Mach 5 test condition with a simple Pitot inlet and demonstrated the devices operating capability. In future work, this novel device will be used to characterise the mass capture and back-pressure capability of a flight-representative scramjet inlet.

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