

Industrial oven improvement for energy reduction and enhanced process performance

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Abstract Industrial ovens consume a considerable amount of energy and have a significant impact on product quality; therefore, improving ovens should be an important objective for manufacturers. This paper presents a novel and practical approach to oven improvement that emphasises both energy reduction and enhanced process performance. The three-phased approach incorporates product understanding, process improvement and process parameter optimisation. Cure understanding is developed using Dynamic Mechanical Analysis (DMA) and CIE-Lch colour tests, which together highlight the impact of temperature variation on cure conversion and resulting product quality. Process improvement encompasses thermodynamic modelling of the oven air to evaluate the impact of insulation on temperature uniformity and system responsiveness. Finally, process parameters, such as temperature, pressure negativity and air flow, are optimised to reduce energy consumption. The methodology has been effectively demonstrated for a 1 MW festoon oven, resulting in an 87.5 % reduction in cooling time, saving 202 h of annual downtime and a reduction in gas consumption by 20–30 %.

Keywords Industrial oven · Manufacturing · Energy saving · Process performance · Cure · Optimisation

Abbreviations

DMAIC	Design, measure, analyse, improve, control
CFD	Computational fluid dynamics
DMA	Dynamic mechanical analysis
DOE	Design of Experiments
x, y, z	Physical locations on web
h	Hour
y	Year
Q	Heat flux (kW)
ρ	Density (kg m^{-3})
C_p	Specific heat capacity ($\text{kJ kg}^{-1} \text{K}^{-1}$)
T	Temperature (K)
t	Time (s)
k	Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
γ	Layer thickness (m)
\dot{m}	Mass flow rate (kg s^{-1})
M	Mass of oven air (kg)
i	Refers to an oven structural component (wall, ceiling or floor)
A	Heat transfer area (m^2)

Introduction

Industrial ovens are commonly used in the manufacturing industry for curing, drying or baking. An oven's performance, compared to the best available practice, can decrease over time due to structural/mechanical degradation, technology advancements or changing process requirements. There is potential for functionality improvement, in terms of energy and process performance, in many existing industrial ovens. Heating applications consume almost 1/5 of all industrial energy (OEERE

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2001), and this study has calculated that typical greenhouse gas emission from a direct gas fired industrial oven is 0.2–0.4 tCO₂e per tonne of product throughput for a 1 MW oven. Site-wide energy saving within heating processes is relatively common throughout the existing literature. Miah et al. (2014) present a decision-making framework for heat integration in production lines to identify heat recovery opportunities. Dörr et al. (2013) discuss a methodology that links energy-saving potential to the improvements for production processes, while Duflou et al. (2012) give an overview of state of the art energy efficiency methods in manufacturing operations. Although potentially beneficial, site-wide process improvement via retrofitting is often unfeasible due to limitations in existing technologies, space availability, layout restrictions, heat losses, disruption to production, financial viability, etc. Reducing energy consumption of oven units offers a focused and feasible approach to energy saving.

The aim of improving industrial oven should be to increase product quality, production efficiency and worker safety, as well as to reduce energy consumption and waste. Process variation of operating conditions has a significant impact on product quality, performance, cost, safety and operational efficiency. The cost reduction associated with lean manufacturing is important for businesses in increasingly competitive markets (Srinivasan 2011). However, manufacturers are more concerned with the quality of their products over the energy consumption, and this prioritisation affects how energy reduction is pursued within industry. Therefore, linking energy and product quality deserves attention in the research. Pathare and Roskill (2016) present quality and energy performance analysis in the food manufacturing industry; however, there is little evidence of emphasis on both dimensions for heating processes in the light manufacturing industry. Understanding of process variation has many benefits and is critical for manufacturers to be competitive. It can be used to develop better products, avoid excess precision in certain aspects of a process, minimise defects, allow for a faster transition from one product to another, deliver cost reduction and reduce scrap (Thornton 2004).

Lu et al. (2012) offer a dual objective framework for optimisation of energy saving and product quality for injection moulding processes. The study has been completed at a laboratory scale to deliver a 10 % energy reduction; however, the conclusion reached is that higher quality can result in higher energy consumption and that there must be a trade-off to satisfy the application needs. Khatir et al. (2013) demonstrate the thermal management of bread baking ovens using CFD (Computational Fluid Dynamics) modelling to minimise energy consumption and improve oven functionality. Khatir et al. (2015) also report laboratory-scale investigations to develop product

understanding and combine this with industrial-scale investigations to thoroughly understand oven performance. Their research highlights the important link between product quality and energy reduction in industrial ovens. Bhanot et al. (2016) also present a framework for industry to analyse the economic and environmental performance of a turning process to maximise benefit to the manufacturer, while Mukherjee et al. (2015) utilised the sustainability footprint method to evaluate methanol production processes, thus incorporating economic, environmental and social performances into the analysis.

Organisations tend to use methods such as Six Sigma and Total Quality Management to improve oven performance (Thornton 2004). These tools can highlight improvement areas and can establish modification plans, which include upgrading equipment or installing additional hardware (Espindle 2011). Pask et al. (2014) show the application of a modified version of Six Sigma's DMAIC (Design, Measure, Analyse, Improve, Control) methodology to reduce energy within industrial ovens, resulting in a decrease in gas consumption in an oven by 29 %. This study, however, is on energy consumption and does not link to product quality.

Product understanding can be used to help identify constraints in an existing process and can highlight areas of potential process improvement. Polymer composites are used in many manufacturing applications, and techniques such as dynamic mechanical analysis (DMA) are used to develop understanding of polymer curing processes (Saba et al. 2016). DMA is a versatile technique that can provide information on the physical changes of a resin which is subjected to a thermal regime. At the same time, it is important to link lab-based DMA findings to product quality on the actual manufacturing line.

This study focuses on oven improvement that involves energy reduction and process performance enhancement. A three-phased improvement approach is presented that includes product understanding, process improvement and process parameter optimisation. An industrial application demonstrates how the approach can be interpreted and applied to a manufacturing scenario.

Methodology

The iterative approach for improving industrial ovens is shown in Fig. 1. The method starts with product understanding before moving to process improvement and then finally looking at process optimisation. Incorporating product quality considerations throughout the improvement process helps to develop process capability, which results in economic benefits for a manufacturer in terms of energy saving and process performance. Ideally, activities should

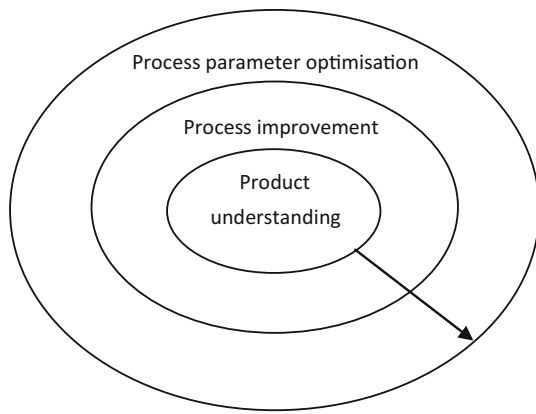


Fig. 1 Iterative approach for oven improvement

be completed sequentially so that changes are made at the correct time during the improvement process. For instance, product understanding can highlight an aspect of oven performance which is underperforming and needs to be improved. Alternatively, optimisation should be completed once manufacturers are confident in the process hardware; optimising process settings before the hardware is changed is not efficient. That being said, in practice, the approach is likely to be an iterative process. This is because of the understanding gained from one phase can highlight areas, overlooked earlier. Developing knowledge of both the process and product can be done in parallel, and oven improvement should be a continuous process. This section details the methodology and the techniques used in the industrial oven case study.

Figure 2 presents a flowchart which interprets three-phased approach (Fig. 1) for industrial oven application. The flowchart starts by evaluating an existing oven system before using this insight to direct product understanding.

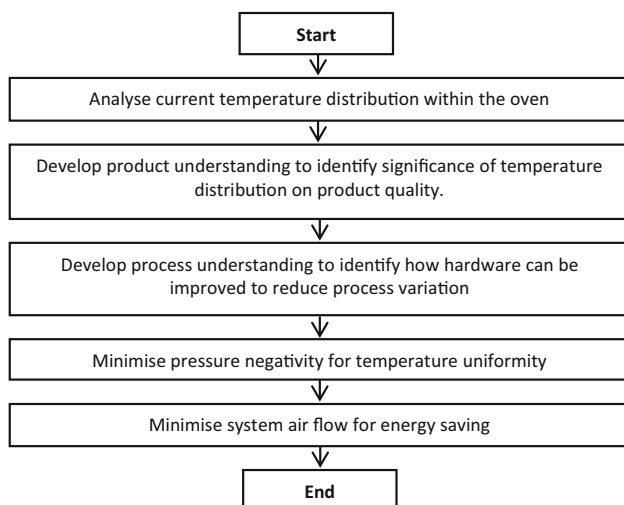


Fig. 2 Process-specific flowchart

The understanding of how process temperature variation affects product quality is used to direct the process improvements that are required. The next step is then to reduce oven pressure negativity and reduce system air flow through process optimisation.

Product understanding

The aim of this phase is to understand what affects product quality, which can be the determining factor for many modification projects. It establishes what is required from the process to deliver a product which performs to specification. This work, generally performed at a laboratory scale using experimental approaches, acts as an enabler for future projects by understanding risks associated with projects or by quantifying potential quality improvements. Establishing this knowledge at the beginning of the improvement approach is beneficial because it enables the right decisions for process improvement and optimisation to be made quickly.

For the industrial application presented in this paper, a number of different techniques are used to develop product understanding. Temperature logging of a product through the oven identifies the actual thermal regime the product is subjected to and highlights the areas of process temperature variation. DMA is used to understand the physical dynamic properties of an adhesive over a thermal process. The CIE-Lch colour test and accompanying free phenol analytical technique are used to give an indication of what the DMA data mean in terms of product quality. Further information on product understanding for the industrial application can be found in “[Process improvement](#)”.

Process improvement

Process improvement addresses the following three aspects of the oven system: system controllability, process variation and energy consumption. This activity looks to develop operability and maximise an oven’s capability under its current process settings. Analysis of the system, through a combination of experimental and computational techniques, evaluates how close to its original specification the current process performs. This can then be developed to establish a way to exceed and enhance the oven’s original capability. Improvements in this section are likely to be the physical changes to the oven system, which can be in the form of upgrading equipment or installing additional hardware. Product understanding can be used to help identify constraints in an existing process and can therefore highlight potential process improvement.

For the industrial application presented in this paper, process improvement takes the form of installing insulation on the inside of the oven walls to reduce the impact of

structural thermal mass on temperature responsiveness. Modelling heat transfer through the existing oven structure can determine the potential advantages in terms of energy saving and reduced process variation. Process improvement can involve installing additional sensors to assist with process control and understanding, which can then generate understanding of product quality, resulting in an iterative approach.

Process parameter optimisation

Process parameter optimisation is the final step in the oven improvement approach. The optimisation procedure questions whether the existing process settings can be altered in order to give benefits to process variability, product quality as well as energy consumption. Optimisation involves detailed analysis of process variables through empirical or theoretical approaches. Energy reduction is a key target in this stage, with the optimisation of process variables often being cost-effective. This is the final stage because optimisation of a process should ideally be completed once the manufacturer is satisfied with the physical setup of the system.

Pask et al. (2014) outline an optimisation methodology for industrial ovens which is applied in the industrial case study. The systematic approach follows Six Sigma principles and applies them to an oven scenario. The approach involves five stages as follows: Define, Measure, Analyse, Improve and Control. The optimisation objective is to establish process settings that minimise energy consumption and improve product quality. All process variables affecting energy consumption and product quality are identified and analysed, such as fans or dampers. Performance data energy consumption and product quality are analysed for different variables to identify optimal settings that best achieve the objective. The oven is then improved to its optimised state and closely monitored.

Case study: improvement to an oven for adhesive resin curing

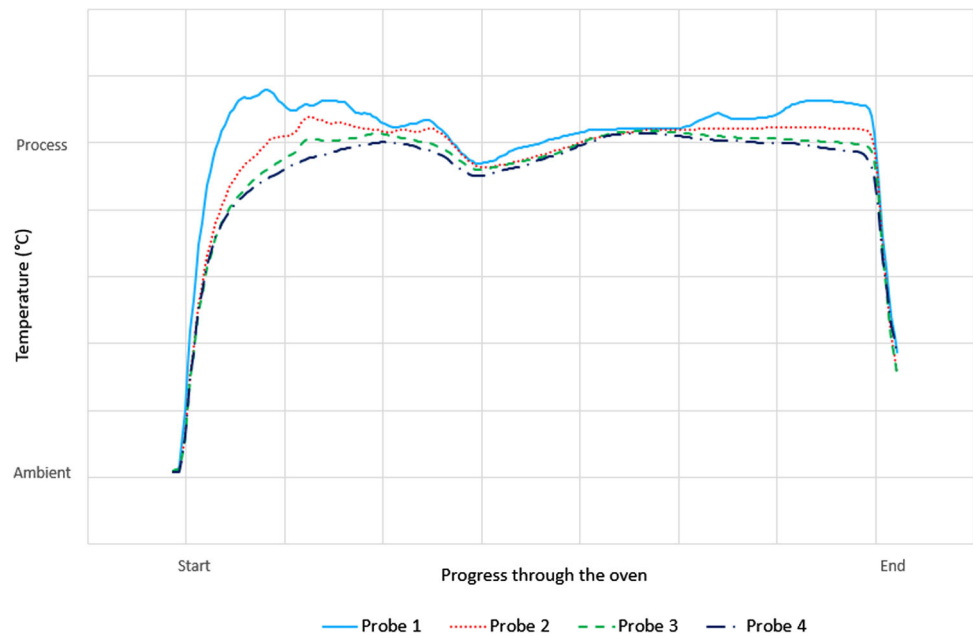
In order to demonstrate the intended use, the approach is applied to an industrial-sized festoon oven that cures a layer of adhesive resin to a backing. Energy is supplied to the oven with direct fired gas burners with fumes exhausted to atmosphere. The 1 MW oven performs its task reliably; however, it is identified as an area of process improvement and energy saving. Greater understanding of the product is required to minimise variability in quality, as well as reducing risks associated with process modifications. The rest of the section details how the approach has been applied to this oven.

Product understanding

A key gap in product understanding is the knowledge of how temperature variation affects adhesive resin curing. Temperature profiling within the industrial oven should be conducted to understand existing process variation. In the given example, this is investigated by additional measurement through four probes attached to the webbed product at periodic vertical intervals. Figure 3 shows the vertical web temperature deviation for one product above and below its set point, with Probe 1 being the highest point on the web, and Probe 4 being the lowest (numerical values have been removed due to confidentiality). It highlights that temperature variation is particularly problematic at the beginning and end of the process.

Cure characterisation is also required to understand the impact of temperature variation on product quality. The cure of a resin is represented on a scale of 0–1, and is a qualitative measure of the relative number of cross links which are formed with respect to complete vitrification of a thermosetting adhesive (Sernek and Kamke 2007). Understanding the cross-linking of polymers can help identify the most appropriate cure strategies (Dickie et al. 1997). In this particular case, the level of cure achieved in the process has not been known and the level of cure to be targeted has also been unclear.

To examine how final temperature affects adhesive cure properties, the adhesive resin has been analysed offline using a combination of two laboratory-scale analytical techniques, Dynamic Mechanical Analysis (DMA) and free phenol/CIE-Lch colour test. DMA provides information on how the physical property of the resin varies after being subjected to different temperature regimes, while the free phenol test is used to relate physical cure properties to the actual manufacturing process. The CIE-Lch colour test can be used to quantify the free phenol test results. Three temperatures have been used to replicate common temperature variation within the oven; x , y and z °C (actual temperatures omitted due to confidentiality), where x °C is the average temperature at the bottom of the oven, y °C at the middle and z °C at the top of the oven. Samples of adhesive-coated film are prepared for both the DMA and free phenol/CIE-Lch colour test. Standard isothermal DMA procedures are followed on samples at each temperature over 180 min. The DMA applies a sinusoidal force measuring the in-phase component (storage modulus) and the out-of-phase component (loss modulus). The storage modulus is an indication of the material's elastic behaviour, and the tan delta (tan D) is ratio of loss to stored energy i.e. 'dampening'. These are commonly used for cure understanding as the hardening of a material changes the elasticity and dampening effects.

Fig. 3 Vertical web temperature profiling

Simultaneously, adhesive-coated samples are heated at matching temperatures in a separate laboratory oven. A free phenol test is conducted on these samples every 10 min. The free phenol experiment involves submerging the coated sample in 2 % mixture of sodium phosphate. If the sample is under-cured, the solution removes the free phenol from the adhesive and a sodium hypochlorite indicator can be used as a visual indication of cure. In order to quantify the level of the phenol in solution, and thus imply the cure conversion, a CIE-Lch colour test is performed on the resulting solution. The CIE-Lch test measures three axis values: *L* axis is the lightness, *c* axis is the saturation and *h* is the hue.

Figure 4 plots the hue data from the CIE-Lch colour test. Hue is measured in degrees, ranging from 0° (red) through 90° (yellow), 180° (green), 270° (blue) and back to 0°. The samples start at yellow/orange before changing to green and then to blue when a higher level of cure is established. Note that, at each temperature, there is a strong correlation between the trend of the hue value and that of the $\tan D$ value. More specifically, it appears that the $\tan D$ peak does not occur until a hue value has settled out above 250°. Therefore, the hue value has been used as a quick method to establish when the $\tan D$ peak has been achieved during online testing.

By investigating three different final temperatures, the study has shown the importance of achieving a uniform temperature profile within the industrial oven. The DMA analysis shows that the $\tan D$ peak, and implied complete cure conversion, falls from 73 min at x °C to 40 min when the oven is set at z °C. As the temperatures x , y and z °C represent a feasible variation in the oven, this study has

demonstrated that the process temperature variation can significantly affect how cured a product is when exiting the oven, and thus can have a significant impact on quality.

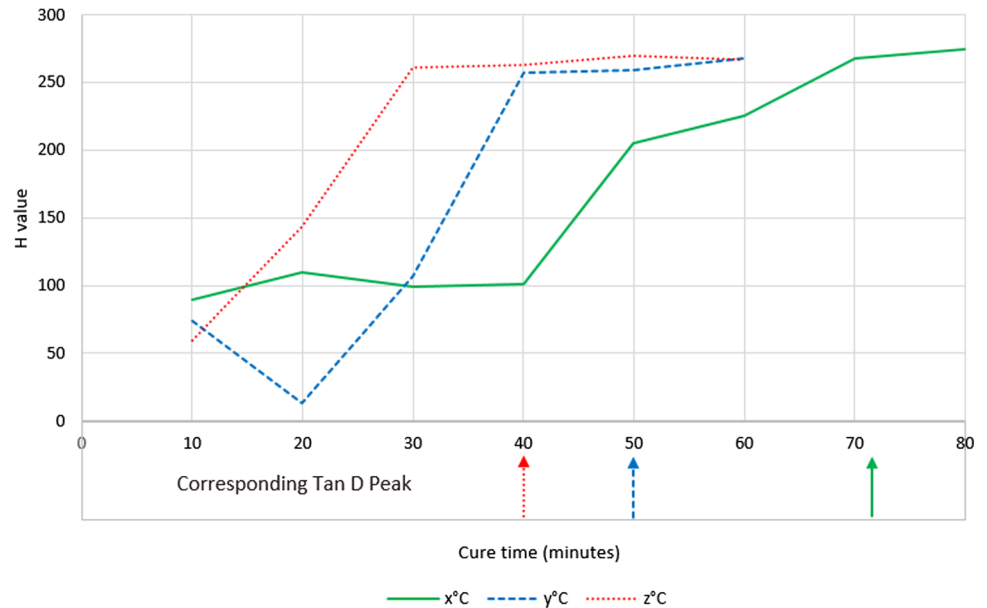
Product understanding has demonstrated an aspect of the process that negatively affects product quality. This can be used to target specific aspects of the process which need to be improved to reduce energy saving and enhance process performance. The combination of the DMA analysis and the free phenol/CIE-Lch colour test has not been presented in the literature before, with traditional cure understanding only using DMA data. The combined method presented in this paper is effective at linking lab-based DMA findings to product quality on the actual manufacturing line, a long standing issue in industrial settings attempting to characterise adhesive cure.

Process improvement

Product understanding highlights the importance of delivering a uniform temperature profile. As well as cross-web variation, another constraint of the system is its inability to quickly change to a new temperature profile. As products with different temperature set points are run continuously after one another, the system's inability to change temperature can result in different temperature profiles for products at the start and middle of a run.

The influence of structural thermal mass reduces the oven's ability to change temperature. This results in long start-up periods and unnecessary downtime during breakdowns. The existing wall structure consists of thermal blockwork, insulated cavity and an external skin. A modification to install an insulation layer to the inside of the

Fig. 4 Results from colour test: H value of each sample and the $\tan D$ values shown below the plot



oven wall is proposed to reduce the impact of structural thermal mass. Along with reducing oven pressure negativity to minimise cold air ingress, insulation would help to develop a tightly controlled repeatable process.

To assess the effect of adding an insulation layer on the heat fluxes across the dimension of the solid oven structure during the heating and the cooling process, a heat transfer model is adopted as shown in Eq. (1). The boundary conditions assume a constant internal oven temperature during the heating process and a constant external ambient air (for walls and the ceiling) or ground (for floor) temperature for both the heating and the cooling process. The initial condition adopted for a heating simulation is an oven wall temperature that is just above ambient air temperature. The heat transfer equation is solved for simulating the heating process first. Once a steady-state temperature is reached, the structure's temperature profile is taken as the initial condition to model the cooling process. For cooling, burners are turned off and the fans replace warm air with ambient air. As a preliminary analysis, the oven air temperature is first assumed to be constant at the ambient temperature throughout the cooling process, which in a second step is replaced by a more realistic treatment as presented later in this section.

$$\rho C_p \frac{dT}{dt} = k \frac{d^2 T}{dy^2}, \quad (1)$$

where ρ is the density (kg m^{-3}), C_p is the specific heat capacity ($\text{kJ kg}^{-1} \text{K}^{-1}$), T is the temperature (K), t is the time (s), k is the thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) and y is the layer thickness (m). Figure 5 presents the model output showing the heating and cooling temperature

profiles for an industrial festoon oven wall with and without an insulation facing (numerical values have been removed for the reasons of confidentiality). Figure 5a, b shows the cross-sectional wall temperature for the existing structure for heating and cooling regimes, whereas Fig. 5c, d shows the same for a wall structure with a layer of insulation on the inside surface. A comparison of Fig. 5a–c demonstrates that the time taken for the structure to reach steady state reduces when insulation is installed: from 10 to 20 h, there is still a considerable change in temperature profile for the existing wall structure, while the insulated system does not have a significant temperature change after 10 h. Energy used to heat the wall structure results in higher supply temperatures to maintain the set point exhaust temperature. Higher supply temperature results in greater temperature variation within the oven and thus negatively affects the product quality variation. A comparison of Fig. 5b–d shows that the time taken for the wall structure to cool is reduced for the insulated system.

Encouraged by the positive effect of insulation suggested by the above preliminary analysis, a more realistic model is adopted to determine the cooling profile of a hot oven in a blow-down operation, when the burner is off and the exhaust and supply fans are fully on. The model included a heat balance equation for the inner-oven space, as shown in Eq. (2).

$$C_p M \frac{dT_a}{dt} = C_p \dot{m} (T_0 - T_a) + Q, \quad (2)$$

where T_a is the oven air temperature (K), T_0 is the inlet (i.e. ambient) air temperature (K), M is the mass of air in the oven (kg), \dot{m} is the mass flow rate of the air that flows through the

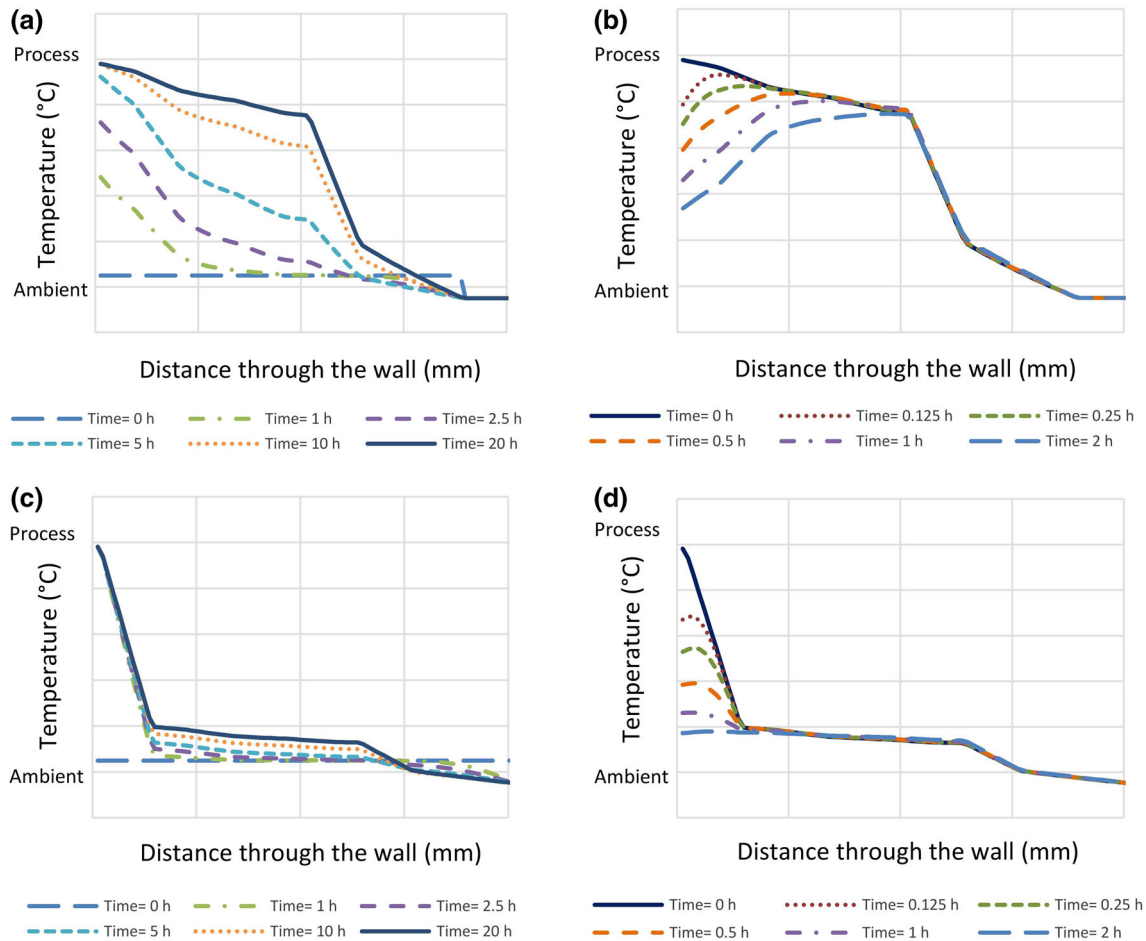


Fig. 5 Heating through the wall structure, **a** heating of existing blockwork, **b** cooling of existing blockwork, **c** heating of insulation faced blockwork, **d** cooling of insulation faced blockwork

oven (kg s^{-1}), C_p is the heat capacity of air ($\text{kJ kg}^{-1} \text{K}^{-1}$) and Q is the total heat flux into the oven from its solid structure (kW). Q can be evaluated by Eq. (3) as

$$Q = \sum_i h_i A_i (T_{s,i} - T_a) \quad (3)$$

where h_i is the heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$), A_i is the heat transfer area (m^2) and $T_{s,i}$ is the temperature at the inner surface (K) of the oven's structure component i such as the wall, ceiling or floor. Together with the heat transfer equation introduced earlier, Eq. (1), which now includes Robin boundary conditions to connect the heat fluxes at the interface between the oven structure and external (ambient) or inner-oven environment, the blow-down cooling process is simulated, with results shown in Fig. 6.

Note that, long cooling periods have a negative effect on production efficiency as operators can only enter the oven after breakages once the temperature is below a safe limit. Figure 6a shows the cooling profile for the existing structure, while Fig. 6b displays the cooling profile for an oven with 50 mm of insulation on the oven walls and floor, both

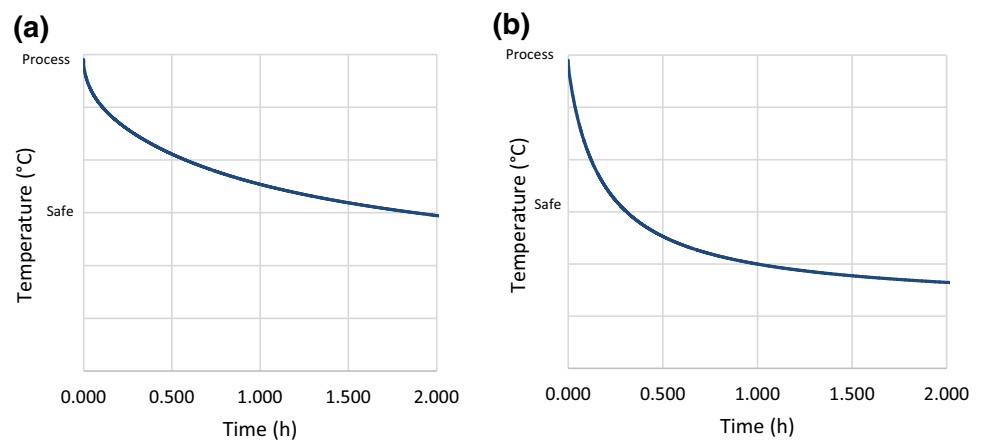
label the process temperature and the safe temperature for oven entry. As can be seen from Fig. 6a, b, the time taken to reach the safe temperature is 2 h for the case without insulation, whereas the insulation reduces it to approximately 15 min. This represents an 87.5 % reduction which can save an estimated 202 h/y downtime.

This analysis shows that the oven structure has a significant impact on oven temperature as heat retained within the structural thermal mass results in long cooling periods. Insulating the walls and floor benefits the operation and productivity of the oven system and also helps to deliver a consistent thermal regime to the product ensuring uniform cure and enhanced product quality. Process improvement enhances the process performance which has a positive economic impact as productivity and results in superior quality product to be manufactured.

Process parameter optimisation

Process parameter optimisation is the final stage of the improvement approach. Pask et al. (2014) present a Six

Fig. 6 Air cooling for an oven with **a** no insulation on inside surfaces, **b** 50-mm insulation on the floor and walls



Sigma DMAIC (design, measure, analyse, improve, control)-based methodology for parameter optimisation that is adapted for this application. When applying the DMAIC methodology to this oven, the aim identified is to establish optimal process parameters to reduce energy consumption by minimising system airflow and to improve temperature uniformity by minimising cold air ingress through the oven slots. Figure 7 displays the process variables within the oven system affecting energy consumption and temperature uniformity including a direct fired gas burner/heater box, three fans (F), five dampers (D) and the ducting/recirculation system. The dashed line passing through the oven represents the web path.

Fans and dampers offer the most reliable and practical way to reduce energy consumption and improve temperature uniformity in this oven system. Experimental analysis of the process highlights that the three fans (supply,

recirculation and exhaust fans) have the largest impact on system air flow. Furthermore, fan control is the most practical option for parameter optimisation because variable speed drives (VSDs) are already installed. Minimising airflow by reducing fan VSD inverter setting (%) is straightforward; however, an optimum oven pressure negativity must also be maintained to ensure that harmful fumes do not exit the oven and to limit the ingress of cold air into the oven, which has a detrimental effect on temperature uniformity. All three fans affect oven negativity which is determined by the supply and exhaust flow rates.

Detailed process optimisation using measurements and control experimentation has been performed for the fan settings for reduced energy consumption and improved temperature uniformity. It suggests to alter inverter settings on the supply, recirculation and exhaust fan while measuring the exhaust and slot flow. Figure 8 shows the

Fig. 7 Oven system under considering; showing fans (F), dampers (D), ducting, and the oven chamber with web path (dashed line)

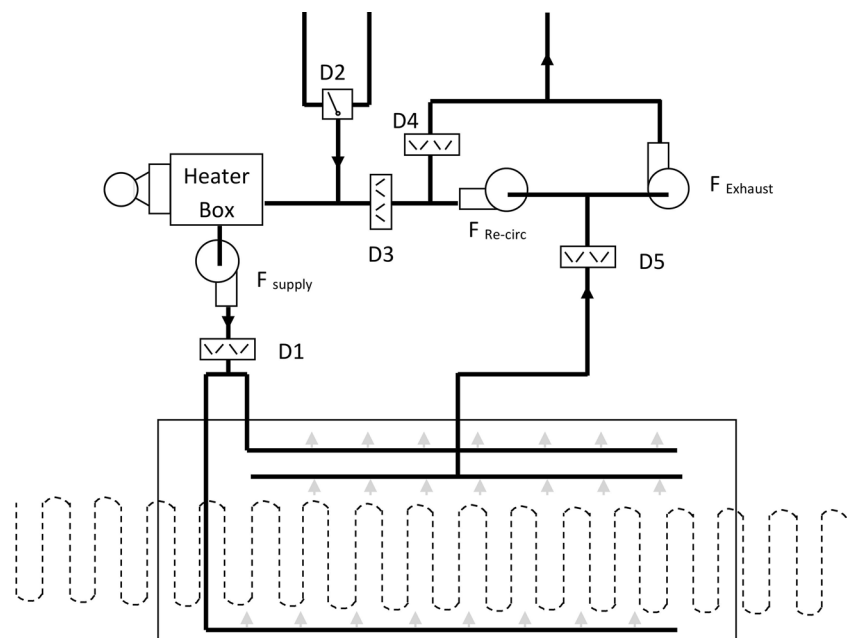
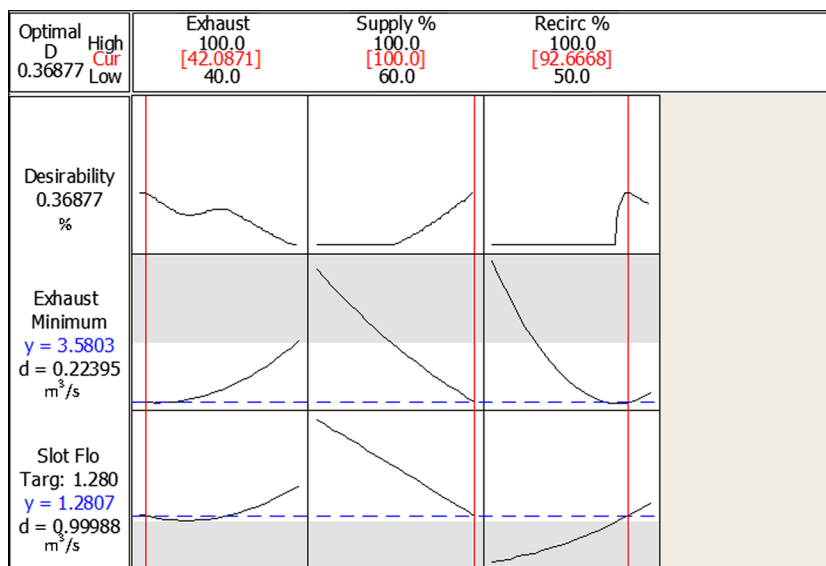


Fig. 8 Optimisation plot for fan speed configuration

resulting optimisation plot, which identifies the fan configuration that delivers the optimum combination of minimum exhaust flow of $0.22 \text{ m}^3/\text{s}$ and a target slot flow of $1.28 \text{ m}^3/\text{s}$. This figure shows nine plots of fan speed against desirability, exhaust flow and slot flow, where D is the desirability of the fan combination (desirability is the extent to which fan configuration reduces the exhaust and target slot flows), y is the target exhaust/slot flow (identified in the charts for all three fans by the dashed blue line) and the red line identifies optimal fan speed. The optimum exhaust fan setting is 42 % (previously set at 80 %), the optimum supply fan setting is 100 % (previously set at 100 %) and the optimum recirculation fan setting is 93 % (previously set at 85 %). These settings decrease airflow through the system by 20–30 % which reduces fuel gas or energy consumption by 20–30 %. Uncertainty with these findings may exist due to the unpredictable nature of the oven negativity, affected by local atmospheric conditions and process temperature.

Precautions, such as consistent atmospheric conditions and process temperature, have been taken to mitigate uncertainty. Instrumental error if any that remains constant throughout measurements is eliminated. The key is to find the changes in the settings needed to make a considerable reduction in energy consumption. The recommended changes in the settings (exhaust and recirculation fans) found are considerable compared to the errors if any. Process parameter optimisation is the final stage of the improvement approach. Along with process improvement and product understanding, an oven system has been developed that consumes less energy and produces higher quality product.

Recommendations

Understanding the interaction between heat energy and the product is necessary in oven improvement projects. Actual and ideal thermal regimes should be compared in the product understanding phase, which can help to evaluate the effectiveness of the oven and identify areas for potential process improvement. Furthermore, it is important for process engineers to interact with both product developers and operators during all the phases of an improvement project. Developers have a detailed knowledge of the product and its components, while operators have greatest familiarity with how the process behaves on a daily basis.

Product quality is often the limiting factor within energy-reducing modifications. Therefore, establishing optimal thermal regimes from both quality and energy perspectives can indicate how oven improvements can be aligned to manufacturing strategy. Key opportunities for process improvement are often in the areas of temperature uniformity, effect of thermal mass and equipment reliability.

Conclusion

This paper presents an approach for industrial manufacturing ovens to reduce energy consumption and enhance product quality, simultaneously. The methodology develops product understanding, process improvement and process parameter optimisation. An iterate approach is practical in industrial scenarios where the knowledge gained from each phase can impact on observations made

previously. The link between product quality and energy consumption should have greater emphasis as it is a vital for manufacturers to tackle their energy consumption. A manufacturer places greater emphasis on generating a profit by creating superior quality products rather than by reducing energy consumption; therefore, emphasising the link between energy and product performance can help more energy-reducing activity within industry.

The iterative approach has been applied to a 1 MW industrial festoon oven that cures a layer of adhesive resin to a backing. Generating product understanding identifies the process conditions necessary to create the desired product, thus highlighting areas of quality improvement. A method of cure characterisation for adhesive resin has been presented which combines DMA and a free phenol/CIE-Lch test. This novel approach gives greater meaning, in terms of product quality, to the lab-based DMA data. The data have shown that a feasible temperature variation within the oven can result in dramatically different cure conversions when material exits the oven; complete cure conversion time falls from 73 to 40 min depending on whether material is at the top or bottom of the oven. Process improvement ensures that system hardware performs as expected and shows ways to enhance the process capability. It also identifies that the oven can be improved by installing an insulation layer to the inside of the oven wall. The effect of insulation has been modelled and found to improve temperature responsiveness, resulting in an 87.5 % reduction in cooling time and an annual downtime saving 202 h. Process parameter optimisation looks to alter the process settings to maximise system performance. Optimal fan settings established can reduce energy consumption by minimising system air flow and oven pressure negativity for better temperature uniformity. The optimisation has the ability to reduce fuel gas consumption by 20–30 %.

Oven improvements should address both energy consumption and process performance simultaneously, and this study demonstrates an effective and practical approach for the manufacturing industry. By providing industrial case study as an example, the iterative approach has been demonstrated effectively at an industrial scale.

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