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Practical Approach for Engineers to Optimise Industrial Ovens for Energy Saving

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Energy saving within the manufacturing sector has a role to play in reducing global energy consumption and green house gas emissions. Despite heating applications being common throughout industry, there is currently no framework that provides practical guidance for energy optimisation in ovens. This paper presents a systematic approach to guide an engineer through five stages of optimisation. It begins with defining the problem and system boundaries, before developing a thorough understanding of the oven system through mass balance and energy analysis as well as identifying all process variables. Analysis of key process variables is conducted to develop process & product understanding and to identify key variables. Improvement of the system and then controlling for full implementation leads to successful conclusion of the project. Application of this methodology has been conducted on curing oven for masking tape manufacture. The optimisation results in a potential 4.7 % annual reduction of the plants energy consumption and off-setting 305 t_eCO_2 from minimal capital expenditure. As the methodology can be tailored to accommodate individual optimisation options for each oven scenario, while still providing a clear pathway, it has potential to reduce energy within the wider manufacturing industry.

1. Introduction

Process heating applications are one of the key energy consuming activities in the manufacturing industry. In the US, it is estimated that 17 % of all industrial energy is used for process heating (EERE, 2013). This paper will focus on industrial ovens, which fall within the heat containing device category of heating applications. Energy saving within industrial ovens can be achieved through effective maintenance procedures (Darabnia and Demichela, 2013), or by applying heat integration to reduce energy demand within heating units (Tovazhnyansky et al., 2011). Alternatively, process optimisation can lead to significant energy saving without the need for excessive capital expenditure, and can be performed on almost any heating application. Thermal optimisation of manufacturing processes has not received a great deal of attention throughout literature; hence the discipline has significant room for development. At a unit process level, optimisation of process parameter settings and controls can typically achieve energy reduction by a factor of 1.1 (Duflou et al., 2012). Techniques such as computational fluid dynamics can be beneficial to determine optimum process parameter settings (Khatir et al., 2013), however they can remain unfeasible for retrofit design in many facilities due to lack of available resource. Furthermore, complete analysis of a process is vital for appropriate selection of process parameters (Apostolos et al., 2013).

In 2005, there was no overarching optimisation method that could be replicated across a wide range of heating applications within different manufacturing operations, with studies tending to lack industrial oven operability analysis and clear optimisation techniques that can be applied in practice (Cheng and Jaluria, 2005). Although procedures have since been established for various individual oven scenarios; whether it is an optimisation algorithm for a paint cure oven (Ashrafizadeh et al., 2012), a multi-objective approach for CFD design (Khatir et al., 2013), or an energy modelling approach that maximises production (Perez and

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Carvalho, 2007), this research area is still underdeveloped with the optimisation tools developed only applicable in narrow fields. Furthermore, existing literature tends not to address the link between product and process understanding with the physical engineering principles of an industrial oven. This should be fundamental for optimisation of commercial ovens in order to reduce risk to safety and product performance, and the research presented will aim to address this.

This paper provides a methodology for engineers to thermally optimise industrial ovens for energy saving. The systematic approach is built on developing a detailed understanding of a particular system, and to then formulate an optimisation plan that alters key process variables to maximise energy saving within process limitations and constraints. This research looks to address oven optimisation from a higher level than previously published work, which can give clarity and guidance to more oven scenarios. An application example is presented to demonstrate the intended use and industrial applicability.

2. Description of the 5 stages

Figure 1 shows the outline to the approach for energy reduction which is adapted on 6 Sigma's DMAIC method to problem solving. It is a well known approach within industry (de Mast and Lokkerbol, 2012) and is in a language that many engineers will be familiar with.

Figure 1: Systematic approach to optimise ovens for energy saving

2.1 **Define**

- Understand oven purpose
- Identify system boundaries
- Develop problem statement

Background knowledge of the oven system is important; it is imperative that that the oven's purpose and physical arrangement are understood. Process and product constraints must be identified early on. System boundaries are to be drawn so the project scope can be defined. A problem statement gives clarity to the ultimate purpose of the optimisation project, and will most likely involve comments referring to safe reduction in energy consumption while retaining product quality.

2.2 **Measure**

- Process stream identification and quantification.
- Mass balance on the system.
- Energy analysis.
- Process variables identified and evaluated.

It is necessary to identify all process streams within the system boundaries, after which a mass balance of the system can be developed. Theoretical or empirical calculations should be conducted for process streams into the system (including air, wet product and solvents etc.), and the streams out of the system (including exhaust gases, water vapour and dry product). An energy analysis of the system is then performed. The theoretical energy required for the process is calculated and then compared to the actual energy consumed. Discrepancies between ideal and actual energy use will give an indication of saving potential. Process variables are identified as 'X' input factors (variables which can be directly controlled e.g. damper position), Intermediate 'I' variables (directly affected by altering X's e.g. humidity within the oven), and 'Y' variables (process outputs e.g. product performance or energy consumption). Evaluation of all variables, through techniques such as cause and effect analysis, can be conducted to identify which variables require further investigation.

2.3 **Analyse**

- Quality baselines set.
- Empirical understanding to develop understanding of X factors and how they affect energy and/or quality outputs, and then label accordingly.
- Process sensitivity analysis.
- Determine process parameters which can be changed that reduce energy whilst retaining quality.

This section improves process and product understanding. The Y's considered should fall within two categories; energy and quality related outputs. For the optimisation to be successful, the engineer has to have a good understanding of both dimensions. Initially, the quality baseline for the product must be established, and in certain instances, critical safety constraints must also be considered.

The stage then looks to understand the impact each X has on the output Y's. In many instances, this knowledge can only be ascertained through empirical studies. The aim is to identify the X's that influence I's, which ultimately influence critical Y's. Input variable are label as X_E, X_{EQ} or X_Q depending on whether they either influence energy (E) or quality (Q) related outputs, or both (EQ). Sensitivity and controllability of the equipment must also be assessed for successfully maximise energy savings.

2.4 **Improve**

- Identify modification options to alter process parameters.
- Safety and risk evaluation.
- Financial assessment; costs, savings and payback periods.
- Finalise modification plan.
- Trail period.

A number of modification scenarios should be generated before identifying the most suitable option. A process hazard analysis must be completed to evaluate the safety implications of making modifications. A business case will then be developed to present the financial benefits of the project by calculating capital expenditure, savings and payback periods. After a modification plan is developed, the final task in this stage is to complete a trial period prove the product quality is not diminished.

2.5 **Control**

- Full implementation.
- Validation period and project evaluation.

The final stage looks to permanently implement the plan from Stage 4. This includes a validation period, where the optimised process is monitored to verify there are no product quality and safety concerns. Once the optimisation has been proven to be successful then it can be implemented in full. The final task is to confirm the projects energy saving and to replicate across additional ovens as necessary.

3. An application example: Cure oven optimisation

3.1 **Define**

The methodology has been applied to a thermal oil curing oven used to cure adhesive on a masking tape web shows the oven flows along with the system boundaries. The oven is controlled by lower explosive level (LEL) analysers which shut the system down if 35 % LEL is reached. The aim of this project is to determine a way in which to optimise the cure oven for energy saving improvements while ensuring the oven's primary purpose does not diminish.

3.2 **Measure**

The process streams into and out of the oven system, as well as the mass flow rate of each stream, is displayed in Figure 2. The flows rates shown were determined through empirical and theoretical calculations. The mass into the system equals the mass out of the system.

The theoretical minimum energy is determined by the minimum safe air flow through the system. An emergency shutdown LEL of 35 % determines minimum dilution air which is required. For the average solvent flow into the oven, the air into the system cannot fall below 3,500 kg/h to keep % LEL at a safe level. Knowing this, the energy minimum required has been calculated as 169 kW using the simple thermodynamic equations. The actual energy consumed within the oven is calculated using the exhaust flow, which requires 909 kW of energy to heat from ambient to set point temperature. Therefore, the theoretical maximum energy saving potential is 740 kW.

All process variables were collected and evaluated. Examples of the X inputs that were considered are fan speeds, damper positions, valve positions and atmospheric conditions. Intermediate variables considered included process air flows, oven pressure, temperature and residence time etc. Output Y variables included things such as natural gas consumption, effective cure of the masking tape product. A cause and effect analysis was conducted for X variables which highlighted that fan speeds and damper positions had the greatest impact on both energy and quality outputs.

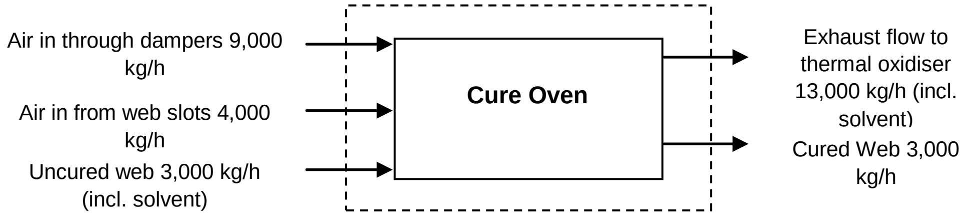

Figure 2: Oven system flows

3.3 **Analyse**

Product quality is determined by temperature and residence time within the oven to ensure that the product is sufficiently cured. Therefore, as any risk to product quality had to be avoided, changes to the line speed and the oven temperature were not considered. The % LEL within the oven and the oven negativity were the key process constraints that had to be considered throughout this stage.

Figure 3 displays the important X variables which were considered. On the diagram, D denotes a damper (both automatically and manually controlled), and F denotes fans. Altering fan speeds was not an option during the experiments as variable speed drives (VSDs) were not installed. Therefore dampers were used to replicate the effect of altering fan speeds. Three experiments were conducted in order to determine the impact of X factors, with Table 1 showing which variables were considered for each experiment.

Experiment 1 highlighted that changes to D5 did not have a significant impact on recirculation flow and that recirculation flow to the air floatation roller was restricted. In this experiment it was shown that D5 was most effective at controlling the exhaust flow from the oven; as can be seen in the main effects plot of Figure 4. Experiment 2 concluded that the optimal oven pressure is -0.24 mbar, as can be seen on Figure 5; optimum pressure is defined when there is the minimal safe quantity of air is drawn into the oven via the slots, 500 kg/h in this example. Experiment 3 ran with product to understand how the LEL responds to reducing air flow though the system. D1 and D4 successfully reduced flow through the system to its optimal value of 9,300 kg/h. To achieve this; D1 is closed fully at 0 %, and D4 is closed to 46°.

Through detailed analysis, the intermediate variables to be altered for process optimisation, while limiting risk to product quality, include reducing the supply air inlet flow and the oven exhaust flow. The X input factors which would impact on these I variables include D1, D4 and F1.

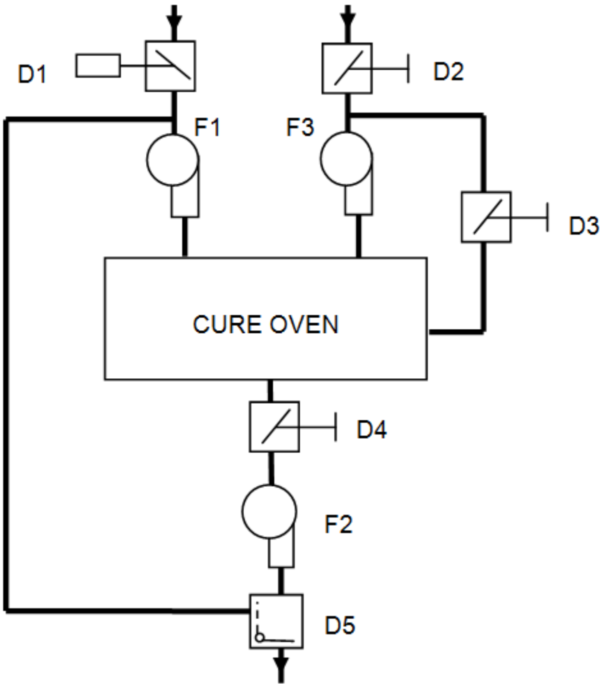

Figure 3: Oven system schematic

Table 1: Variables considered in experiment 1, 2 & 3

	Experiment 1	Experiment 2	Experiment 3
X's factors	D1, D2, D3 and D5	D5	D1, D4
I variables	Exhaust flow, recirculation flow, oven pressure, supply air flow	Exhaust flow, recirculation flow, oven pressure, web entrance and exit slot flow	Exhaust flow, recirculation flow, oven pressure, web entrance and exit slot flow, % LEL

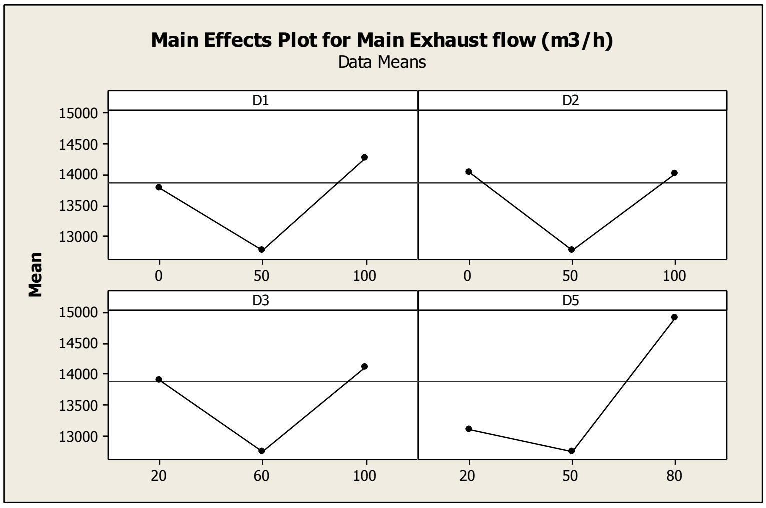

Figure 4: Main effects plot for main exhaust flow (m^3/h)

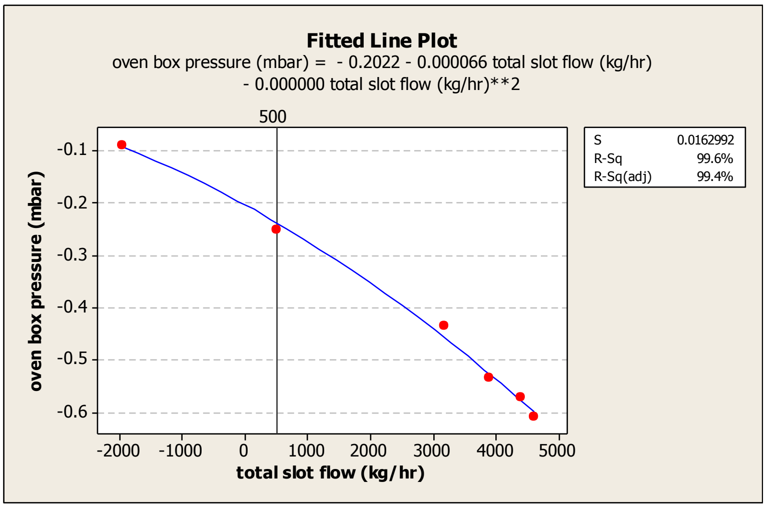

Figure 5: Fitted line plot of oven pressure (mbar) vs. total slot flow (kg/h)

3.4 **Improve**

A number of modification options were considered, and it was decided that three X variables (D1, D4 and F1) will be changed to reduce air flow through the system. The modification plan outlines that D1 will be up graded and set at 0 % (closed) during production mode, and at 100 % (open) during emergency shutdown mode. D4 will be upgraded to and set to 46° during production and set to 0° (open) during emergency shutdown. F1 will be off during production mode, but switched on for emergency shutdown. A Process Hazard Assessment was conducted to ensure the modification will not cause any unintended safety implication. Reducing the flow through the system will raise the average % LEL of all products by 4.8 %. Cumulative annual energy saving across all products is 1,658,000 kWh which represents a 4.7 % reduction on the plants total energy, and is equivalent to offsetting 305 t_eCO_2. The financial cost of the modification is small and a payback period of 4 months is predicted. Trials were conducted on high volume, high solvent product to verify that the optimisation did not diminish product quality. Furthermore a laboratory testing proved the modification could be implemented without affecting product quality.

3.5 **Control**

Implementation is required with a two month validation period to verify the modification. Following this, documents such as start-up/shutdown procedures or PIDs must be updated. Evaluation of actual vs. calculated savings is to be conducted before the project is closed.

4. Recommendations

To reduce total air flow through the system it is recommended that the engineer should determine the limiting variable for reducing the total inlet flow early on. Collecting data to define a baseline of the limiting variable for all products is useful, as is identifying the most sensitive product. Calculation of minimum acceptable inlet air flow rate acceptable and validation this with on-line experiments is necessary. Determine optimum oven pressure is also vital. Although the case study presented looks to reduce overall air flow there are alternative methods that this research's systematic approach could be applied to, such as; to increase heat transfer coefficient of the oven so faster drying rates can be attained, to optimise the temperature and residence time based on drying or cure simulation, or to balance internal air flows.

5. Conclusion

Energy reduction within the manufacturing sector has a role to play in reducing global energy consumption now and in the future. The research presented addresses the energy consumption of industrial ovens, which use a considerable proportion of energy associated within manufacturing. The systematic methodology guides an engineer from the basic understanding of an oven to optimisation for energy saving. The stages include define, measure, analyse, improve and control. Combining process & product understanding with consideration of physical and engineering constraints is a powerful tool which can deliver significant energy savings. This approach has been applied to a curing oven for masking tape production at a 3M facility in the UK. The optimisation plan consisted of reducing air flow through the system by altering process parameters, resulting in a predicted annual reduction of 305 t_eCO_2 being emitted. The methodology is now being applied to additional ovens across 3M facilities in the UK. This systematic approach can be tailored to accommodate individual optimisation options, while still providing a clear pathway. As such, there is potential for such a methodology to reduce energy within other 3M facilities and the wider manufacturing industry.

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