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Achieving Operational Excellence for Industrial Baking Ovens

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Abstract

A series of experiments were performed on industrial baking ovens across five confectionery manufacturing sites around the world. The impact of different operating parameters such as air and fuel flowrates, oven temperature, exhaust flowrates and ambient temperature etc., on the product quality and overall oven performance were investigated. The energy flows through the baking oven were modelled using experimentally determined inputs to estimate the reduction in heat losses. A step change in operational efficiency was achieved through the study delivering 8.5% improvement in the oven performance. On average, 92 tonnes/annum of CO2 were saved from each oven. An additional 7% efficiency improvement was observed by integrating the baking oven with a heat recovery technology saving circa £16k in fuel cost annually from a single oven. The observations and learnings from the work are not limited to baking ovens only, but can also be applied to other food manufacturing processes such as frying, broiling, roasting or grilling.

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1. Introduction

Confectionery is a large global industry currently valued at around $200 bn. Energy wastage in confectionary manufacturing processes is an ubiquitous challenge [1–4]. Processes that require heat, in particular baking, roasting or drying, on average accounts for between 4-10% of a food manufacturing factory's overall annual energy usage. Most of these processes are over-engineered to an extent that the efficiency is compromised. For example, the energy efficiency of an average wafer baking machine is circa 35%. Hence, nearly two-thrid of the total energy cost of wafer production is lost to atmospheric discharge at 150-250ºC. Due to the increasing global population and consequently raised confectionary consumption, the energy demand in confectionary manufacturing sector is expected to continue to rise in the future [3], [5–7]. This forecasted increase in confectionery consumption will exacerbate the energy losses over the next 5 to 10 years. In addition to the energy cost, the energy losses are also proportional to CO_2 emissions and therefore, increases the environmental concern associated with confectionary manufacturing. Most wafer baking ovens currently used in the confectionary sector are based on old designs and operates at low efficiencies, as indicated earlier. The energy losses in wafer baking can be reduced by either improving the baking oven/process itself or by reusing the waste heat emitted from the oven.

For instance, Emmanuel Purlis [8] presented a theoretical approach for optimal design of baking processes. The work establishes a method to obtain feasible heating strategies that ensures minimum thermal input to the product. The work also provides a balance between the baking temperatures and heat transfer coefficient that can help to establish optimum conditions and to design ovens with enhanced efficiencies. Paton et al. [9] presented a methodology to quantify energy required for baking and to analyse breakdown of losses. The authors conducted computational fluid dynamics (CFD) analysis and optimisation along with establishing the energy flows in the oven to determine potential for energy savings. Mondal and Datta [10] reviewed the experimental and mathematical studies on profiling of temperature, moisture content, pore volume, expansion ratio for bread baking technology. Pantaleo et al. examined an intermittent waste heat recovery system for coffee roasting by means of organic rankine cycle (ORC) [11]. The study also compared the output for different types of working fluids used in the ORC. Aneke et al. compared 5 different configurations of ORC systems for waste heat recovery from potato crisp fryer [12]. Waste heat recovery has been extensively investigated in the recent past for various industrial sectors [13-15]. However, there are only a handful of studies that covers food manufacturing sector, particularly for baking sector.

The standard operational practices of the industrial wafer baking ovens involving high volume of air flow to maintain food standards and equipment safety have not been justified scientifically. This study investigates the opprotunities for improving energy efficiency of a baking process by optimising the operating conditions of the baking oven. It also investigates integrating a heat recovery unit with the baking oven to exploit the full potential of energy savings from an industrial-scale baking process. The work presents a systematic methodology for evolving energy saving approaches for a food manufacturing process. The observations and findings from this study are not partial to the food and baking industry specifically but can also be applied to a number of other similar energy intensive manufacturing processes.

2. Materials and Methods

A baking oven, manufacturing flat rectangular wafer sheets, available at an UK based confectionary manufacturing site was used to study the opportunities for optimising operational parameters of the overall baking process. Figure 1 shows a typical industrial-scale baking oven. The batter is fed into a chain of rectangular baking plates that are fixed in tong frames. These baking plates are heated using triangular burners underneath as they are transported through the length of the oven on grease bearings. The triangular burners are fed with ready-to-burn air (also called combustion air) and fuel mixture produced in an air-fuel mixing device. Baking plate temperature or the set point temperature regulates the quantity of air required for combustion process.

The gas/fuel flow rate (volume) is determined by the combustion air flow rate (volume). A Zero Pressure Regulator serves to keep the air-fuel mixture constant by allowing the required quantity of fuel to be provided for any quantity of combustion air. A secondary air flow enters the oven through the side walls to keep the oven walls cool and to protect the bearings from overheating. The products of combustion as well as the baking vapours are carried away through the roof into the open air by means of an emission extraction unit with an extractor fan running at 40Hz. The fan is monitored by a differential pressure control device.

The oven performance is calculated in terms of fuel usage for producing unit weight of wafer. This is represented as the oven productivity and is determined by Equation (1).

$$\mu_{baking} = \frac{\dot{Q}_{fuel}}{\dot{\omega}_{wafer}} \tag{1}$$

Where, $\dot{Q}_{fuel}$ is energy used (in kWh) by the oven over a certain time and $\dot{\omega}_{wafer}$ is the wafer output (in kilograms) during the same time.

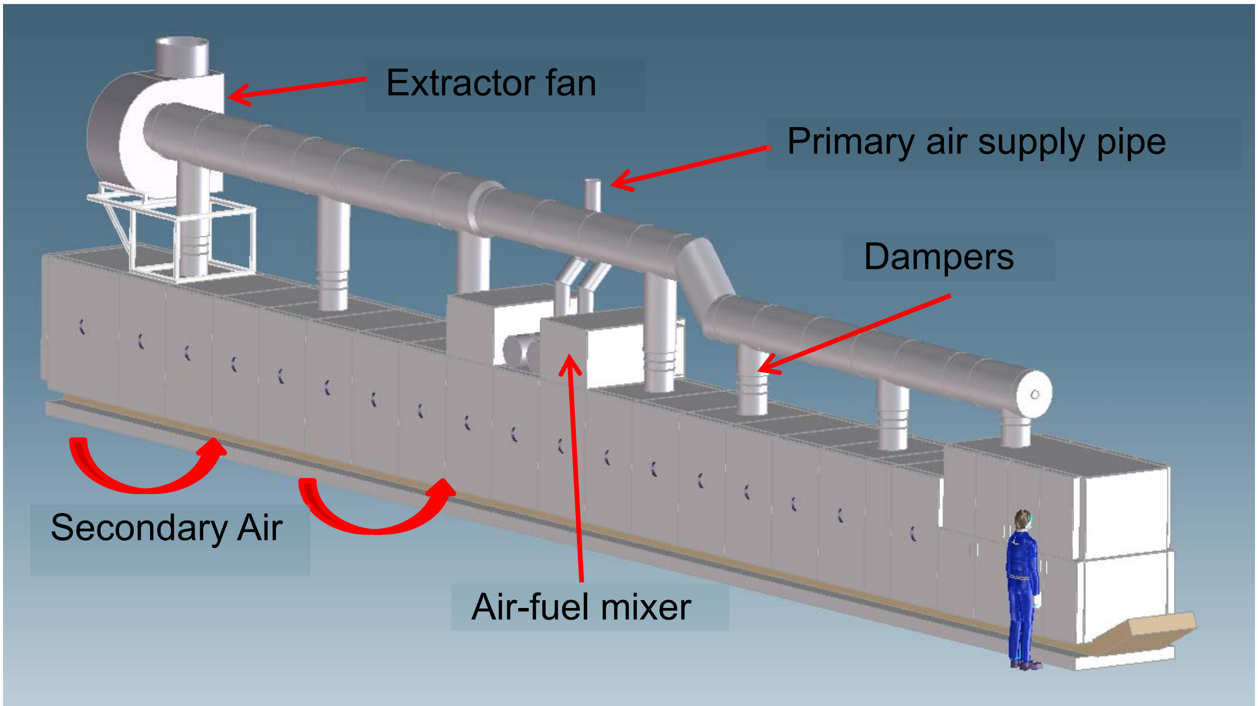

Fig.1. Schematic diagram of an industrial–scale wafer baking oven.

The experiments involved measuring air and fuel flows into the oven, exhaust flow, temperature and composition. A Testo 417 Anemometer and Dwyer 160F-18 pitot tube was used to measure the air and exhaust flowrates. The exhaust composition and temperature were measured by a Drager X-am 5600 Basic flue gas analyser and Testo 925 Channel thermometer, respectively. Omega HH374- 4 channel temperature data loggers were installed at different points across the oven to measure changes in temperature distribution in the oven caused by the experiments. The heat recovery experiments were conducted on a pilot-scale baking oven (scaled-down version of the industrial baking oven) to test a novel air-to-air low temperature waste heat recovery technology; used to preheat the oven's combustion air using its exhaust gases.

A detailed schematic diagram of the pilot-scale wafer baking oven is available in a previous work [16]. The combustion air was heated from ambient to 105°C using a 25 kW electric resistance heater. In a real system, a heat exchanger will be used to raise combustion air temperature by using the heat from the oven's exhaust gases. This heat exchanger unit will be designed to preheat the combustion air up to temperatures 10°C lower than the heating medium which is the exhaust gases in this case. A bespoke controller unit was used to increase and control the combustion air temperature. Figures 2 shows the pilot-scale baking oven used for experiments, the installed electric resistance heater and control system.

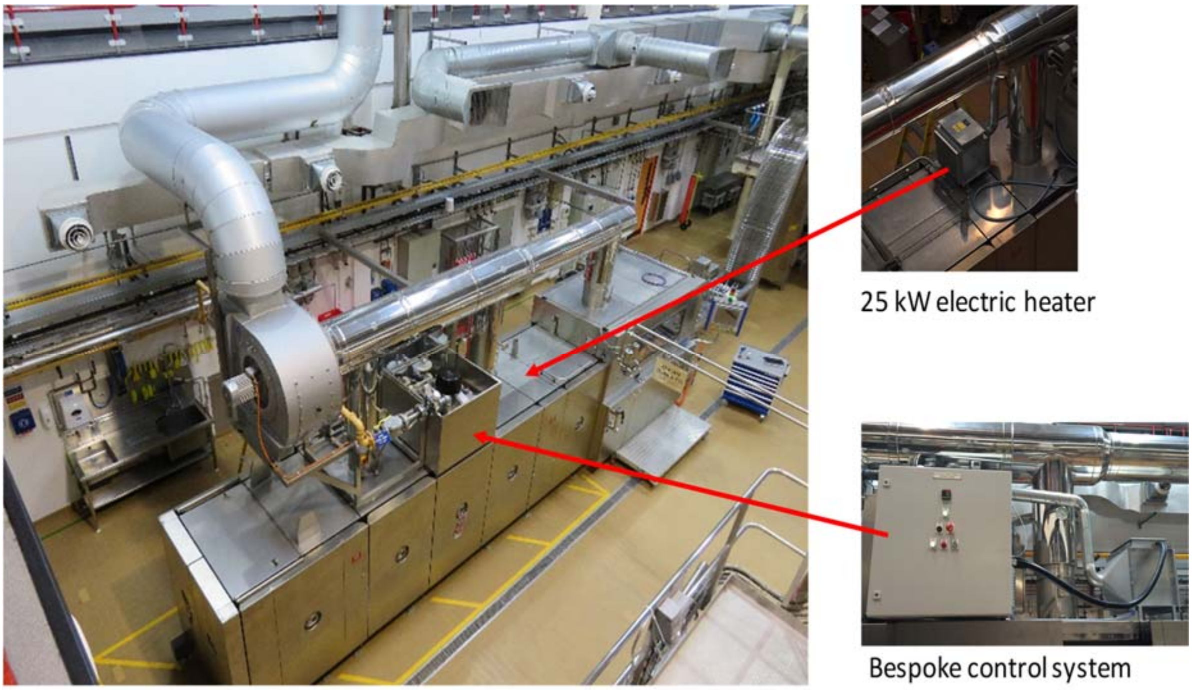

Figure 2: Pilot-scale baking oven with electric resistance duct heater and control system.

Effectiveness of the real (with heat recovery) combustion air preheating system is calculated by Equation (2).

$$\eta_{combustion\ air\ preheating} = \frac{\dot{Q}_{gas\ saved,\ Oven}}{\dot{Q}_{exhaust}} \tag{2}$$

Where, $\dot{Q}_{gas\ saved,\ Oven}$ is the reduced gas consumption rate, and $\dot{Q}_{exhaust}$ is the rate at which the recoverable waste heat is released from the exhaust of a single oven.

Temperature data loggers were placed at different locations in the oven to monitor the temperature rise while conducting experiments. Figure 3 shows the points on the oven where the temperature loggers were fixed.

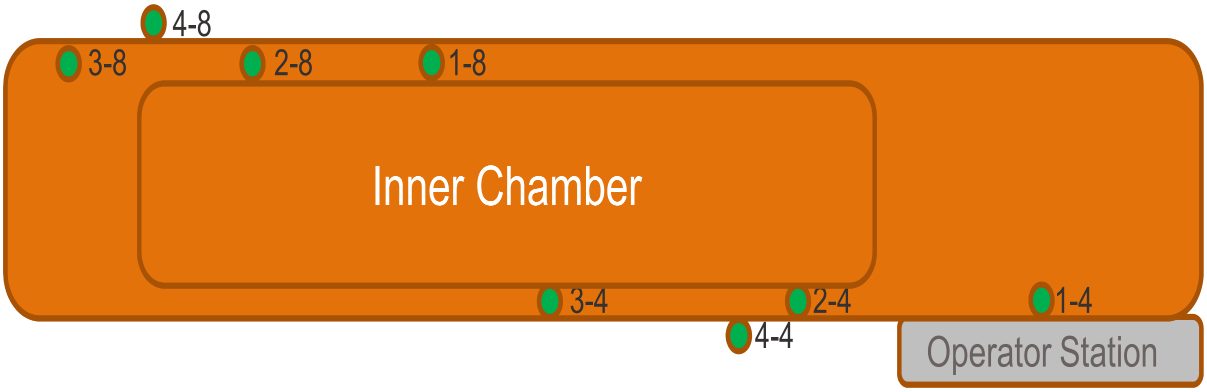

Figure 3: Location of the temperature data loggers installed for temperature mapping of the oven.

3. Results and discussions

3.1 Optimisation and combustion air preheating trials

The control mechanism of the baking oven operates on maintaining a constant baking plate set point temperature predetermined for different recipes of batter. It is fundamental to keep the inner environment of the baking oven hot to avoid heat transfer or heat loss from the baking plates to the air surrounding the baking plates inside the oven. However, the secondary air flow fed into the oven at ambient temperature to cool its side walls and bearings dilutes the hot air, consisting of products of combustion and vapour, inside the oven and therefore also causes unwanted cooling of the baking plates. This impacts the productivity of the oven since more fuel needs to be burnt to compensate for the heat loses while maintaining the required set point temperature.

A suggested solution is to use high temperature bearings and reduce the secondary air flow. This is done by decreasing the extractor fan speed and closing the dampers located at vertical exhaust ducts. Figure 4 shows the variation in the oven's fuel consumption rate with the secondary air flow; represented by damper positions and extractor fan speed.

Figure 4: Effect of extractor fan speed on the fuel consumption rate.

The exhaust flow rate and composition are measured before and after closing the dampers and reducing the fan speed. It was estimated that a 25% reduction in fan speed along with closing the dampers decreases the secondary air flow by 30-35%. This significantly reduces the dilution of hot products of combustion inside the oven and yields an overall fuel savings of 8.5%. The readings from the temperature data loggers indicate that the oven temperature does increase after the secondary air flow is reduced. However, the temperatures does not rise beyond the recommended safety limits. A further 25% drop in fan speed (total 50% drop) reduced the secondary air flow rate by 60-65% and resulted in approximately 15% fuel savings. The trials at 50% fan speed reduction showed promising results in terms of fuel consumption however, it was discontinued due to high oven side wall temperatures achieved shortly after the changes. Addition of adequate thermal insulation to the oven side walls can overcome the issue and will also reduce the radiation losses through the oven walls. Figure 5 shows the results from temperature mapping of the oven during the experiments. It was also observed during the trials that the temperature distribution across the length of the oven became more uniform thus removing the small pockets of low temperatures.

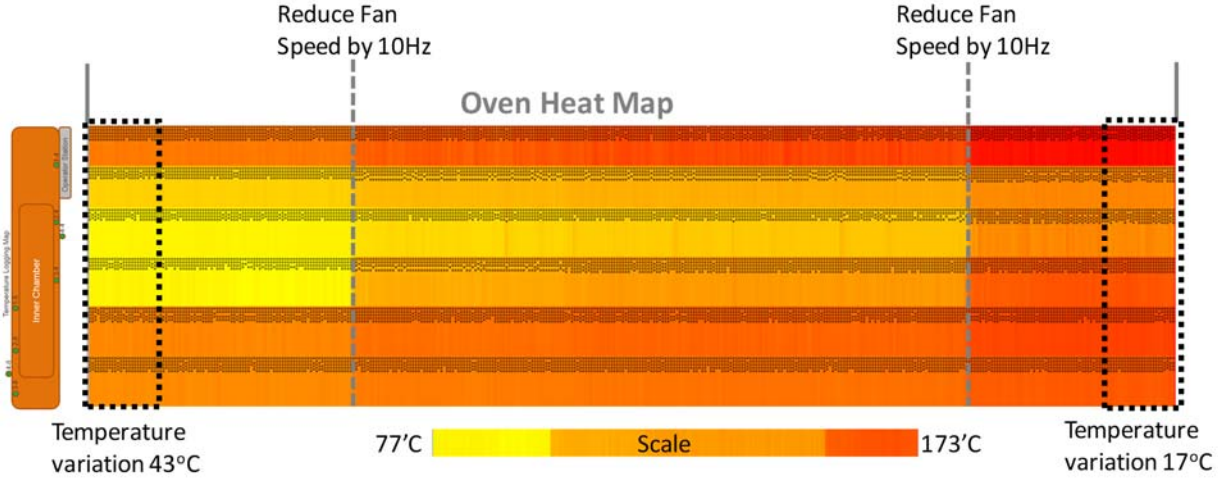

Figure 5: Temperature distribution observed across the oven during trials.

The optimisation trials were repeated on various other industrial-scale wafer baking ovens with similar design at different confectionary manufacturing sites situated internationally. A fuel saving of 7-9% was observed during the international trials as a result of 25-31% reduction in extract fan speed or 30-35% reduction in secondary air flow rate. The observations from the trials are summarised in Table 1.

Table 1.Results from optimisation trials conducted on industrial baking ovens.

Parameter	Units	Oven 1	Oven 2	Oven 3	Oven 4	Oven 5
Baseline Gas Consumption	m^3/hr	25.7	68	71	75.5	22.0
Reduction in fan speed	%	25	31.25	25	25	25
Gas consumption after change	m^3/hr	23.9	61.8	64.7	69.3	20.2
Fuel savings	%	7	9	8.8	8.1	8.1

During the preheating trials, the combustion air temperature of the pilot-scale baking oven was gradually raised from 30°C to 105°C using the electric heater. The preheating resulted in increasing the flame temperature and consequently the baking plate temperature. Thus, triggering the oven's control system to reduce the fuel supply in order to maintain the baking plates at the set point temperature. The baseline fuel consumption without combustion air preheating was recorded as 27.69 Nm^3 or 306.12 kWh. The oven produced 90 kg wafer per hour with a productivity of 3.4 kWh per kg of wafer. A net saving of circa 4% in the average fuel consumption was observed during the preheating trials. It was observed from the experiments that every 19°C rise in the oven's combustion air temperature saved approximately 1% of fuel.

The burner flame colour indicates the quality of air-fuel mixture and thus, the fuel combustion efficiency of the burner system. A bluish flame with yellow tip is the recommended flame colour as it indicates complete combustion of the fuel. Whereas, a complete yellow flame shows rich mixture being fed to the burners causing fuel wastage. This can be fixed by resetting the air-fuel mixer valve position. The flame colour was thoroughly monitored during the trials in order to understand the impact of the changes made in oven's operating conditions. The composition of the oven's exhaust gases were recorded after each change was made to trace the quantity of unburnt combustible gases as a sign of incomplete combustion. The moisture content, texture, weight, colour, temperature and size of the wafer produced during the experiments were also monitored to detect any deviation or degradation in the product quality. All these quality checks revealed no fuel losses through the exhaust and no negative impact on the product quality. A more detailed information on the preheating experiment including flame and product quality can be found in Mukherjee et. al. [16].

3.2 Overall energy, cost and environmental savings

The findings on fuel saving potential of the combustion air preheating system, obtained during the pilot-scale experiments, were applied on an industrial-scale baking oven. An actual heat recovery system can preheat the combustion air up to temperatures 10°C below the exhaust gas temperature. It is recommended that the oven operating conditions should be optimised before designing the heat recovery system. This is because the amount of waste heat available for recovery in the exhaust (indicated by exhaust temperature, flowrate, moisture content) may change after optimisation. In the current study, a 8°C rise from 165°C in the exhaust temperature was detected after reducing the secondary air flow. This allows to preheat the combustion air to 163°C and save ~7% fuel consumption. Tables 2 shows the key performance indicators of the industrial-scale wafer baking oven and the potential savings that can be achieved through reducing the secondary air flow and heat recovery. It is seen that the combined heat recovery and reduction in secondary air flow can save 15.5% or 910 MWh of fuel per year based on 7000 hours of operations. The combination can save the annual fuel cost by £16,308 considering 1.8p/kWh of fuel price and reduce CO_2 emissions by 167 tonnes per year from a single oven.

Table 2.Summary of secondary air flow reduction and heat recovery.

Parameter	Units	Baseline	After secondary air flow reduction	After heat recovery	Optimisation and heat recovery combined
Fuel consumption	kWh	835	764	776	705
Annual operational hours	h/yr	7,000	7,000	7,000	7,000
Wafer production	Kg/h	251	251	251	251
Extractor fan speed	Hz	40	30	30	30
Productivity	kWh/Kg	3.32	3.04	3.08	2.8
Annual fuel cost	£/yr	105,210	96,267	97,845	88,902
Annual CO_2 emissions	Tonnes/yr	1075	983	1,000	912
Fuel savings	%	-	8.5	7	15.5
Annual energy savings	MWh	-	497	413	910
Annual cost savings	£	-	8,943	7,365	16,308
Annual CO_2 savings	Tonnes/yr	-	92	75	167

4. Conclusion

An experimental analysis was conducted on wafer baking ovens to optimise the operating conditions and test a novel gas-to-gas heat recovery solution. The optimisation trials indicate an 8.5% improvement in oven efficiency by achieving operational excellence, whereas, the heat recovery solutions show a further 7% fuel savings. A combined optimisation and heat recovery could reduce the annual fuel cost by £16,308 and can avoid 167 tonnes of CO_2 emissions annually from a single baking oven. The findings from this study are not limited to wafer baking only, but can also be used for other low temperature food manufacturing processes such as roasting or drying.

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