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Waste heat recovery from industrial baking ovens

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Abstract

Under this work, a system level energy model of an industrial-scale baking oven with an integrated waste heat recovery unit is developed using experimentally determined inputs to estimate the potential benefits of a gas-to-gas heat recovery system. This work has demonstrated that at least 4% savings in the oven fuel consumption can be achieved, reducing the annual running costs by £4,207. An environmental assessment indicates reduction of circa 43 tonnes in CO_2 emissions per annum. The study also provides a systematic methodology to test low temperature gas-to-gas heat recovery technology for food manufacturing process.

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Keywords: Waste heat recovery; Baking oven, Energy efficiency, gas-to-gas heat transfer, low temperature heat recovery

1. Introduction

The rising environmental concerns associated with burning fossil fuels have impelled decision makers internationally to introduce policies for mitigating greenhouse gas (GHG) emissions. The strict national and international regulations on carbon reduction and ever-increasing costs of fossil fuels have urged processing industries worldwide to search for alternative technologies to reduce their fuel consumptions and emissions. Industries such as oil and gas, chemical, iron and steel, cement etc. have always been considered major industrial polluters. Studies

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indicate that apart from the above listed industries, the food and drink sector also has a major role to play on energy usage and emissions [1]. In the UK, the food manufacturing and processing industry accounts for 16% of the total manufacturing turnover making it the largest manufacturing sector ahead of aerospace and automotive combined [2]. It consumes 12% of the total energy used by UK's industrial sector [3] and emits approximately 7 million tonnes of CO_2 per annum [4].

The demand and hence the production of food and beverage products is unlikely to drop in future due to an ever-growing population [5]. Therefore, it is important to emphasise reducing energy consumption by improving energy efficiency of the production processes. Most food manufacturing processes involve a heat supply, which often comes from burning natural gas. A substantial proportion of this heat is discharged with the exhaust gases at 150-250°C, aslo termed as waste heat. The UK's food and drink sector emits circa 2.8 TWh of recoverable waste heat into the environment annually [6]. Re-using this waste heat stream through low grade waste heat recovery systems could significantly increase the overall efficiency of food manufactuing processes.

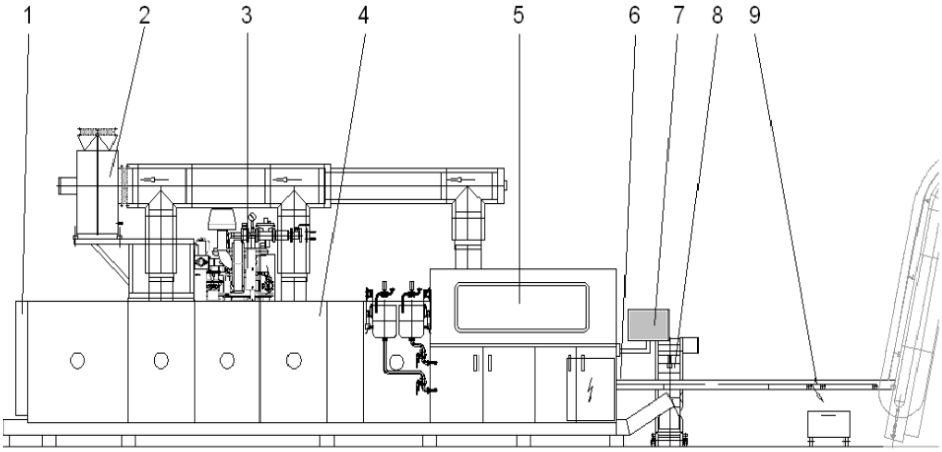
An existing low-grade waste heat recovery technology is gas-to-liquid recovery, which produces hot water from the recovered heat. The hot water can be used for various purposes such as space heating and cleaning operations within the factory. The performance of such heat recovery system is completely dependent on the hot water demand, which can fluctuate throughout the year due to various reasons such as seasonal variations and changes in production levels. Moreover, hot water production from waste heat available from food manufacturing processes is not as favourable if a combined heat and power (CHP) system is already in place, which can serve the same purpose more economically compared to the former. A possible alternate application to reuse the waste heat, other than hot water production, is to pre-heat the air used to produce the fuel-air mixer (also called the combustion air). Preheating of combustion air has been successfully tested in other manufactring industries, transport industry and power generation sector [7-10]. However, there is no study available to the best of the authors knowledge which evaluates the suitability of such technology specifically for food manufacturing processes. This study investigates the feasibility of a novel low temperature gas-to-gas heat recovery system for food manufacturing process.

2. Methodology

Food manufacturing processes involve energy intensive operarions such as baking, frying, roasting, boiling etc. In the current work, a baking process was chosen to evaluate the performance of combustion air preheating technology in food manufacturing. The baking ovens used for conducting experiments were provided by a large confectionary manufaturer. Only about one-third of the total energy supplied to these ovens adds value to the final product. The remaining two-thirds is discharged with the exhaust gases at circa 170°C and therefore making the baking process and ovens perfectly suitable for this study. A detailed description of the baking oven is given in Section 2.1.

2.1. Baking Machine Description

An automatic wafer baking pilot oven shown in Figure 1, is used in this study for experiments and analysis. This oven is used for fully automatic production of flat rectangular wafer sheets. The batter consisting of water, flour and flavouring ingredients is poured onto baking plates fixed in tong frames in the batter depositing station. The baking tongs are linked in a baking tong chain that revolves over bearings across the length of the baking machine. The entire baking plate surface is heated to maintain a steady temperature of 165°C (also called the set point temperature) by the means of triangular burners located under the baking tong chain as it is transported through the oven. The burners are supplied with a mixture of natural gas and ambient air (also called primary air supply) produced in a gas-air mixing device. The burners are controlled through modulation, depending on the heat requirements. The temperature of the baking tongs is used as a correcting variable for fuel supply. The burner blower speed controls the gas-air mixture inlet. The burner blower is controlled by a frequency regulator which reacts to the contactless measurement of the baking plate temperature by a pyrometer. Baking plate temperature regulates the quantity of air required for combustion process. The gas flow rate (volume) is determined by the air flow rate (volume). A Zero Pressure Regulator serves to keep the gas-air mixture constant by allowing the correct quantity of gas to be provided for any given quantity of air.



1. Service door 2. Emission extraction unit 3. Burner device 4. Baking space 5. Batter depositing station
6. Wafer take-off station 7. Control pane 8. Waste scraper 9. Wafer inspection device

Fig.1. Schematic diagram of a wafer baking pilot oven with labels.

After the baking operation, the wafer sheets are removed in the wafer sheet take-off station. Here, a sheet take-off star removes the wafer sheets and forwards them to the further processing line. Cooling air (secondary air supply) is supplied through the sidewalls of the machine to protect the bearings from overheating. The products of combustion and cooling air are continuously extracted together with the baking vapours through an emission extraction unit. The extractor operates at 40 Hz (1160 rpm) and is monitored by a differential pressure control device.

2.2. Primary air preheating unit

During normal operations, the primary air is supplied to the fuel-air mixer of the oven at ambient conditions. During the trials, the ambient air temperature was 30°C. To examine the effects of primary air preheating on the oven performance, a 25 kW electric resistance heater, as shown in Figure 2a, was installed on the primary air supply duct to pre-heat the air up to 105°C. The air temperature was controlled using a bespoke control system, shown in Figure 2b, installed to provide upper limit cut out for the electric heater and to ensure safe limits for differential pressure sensing.

(a)

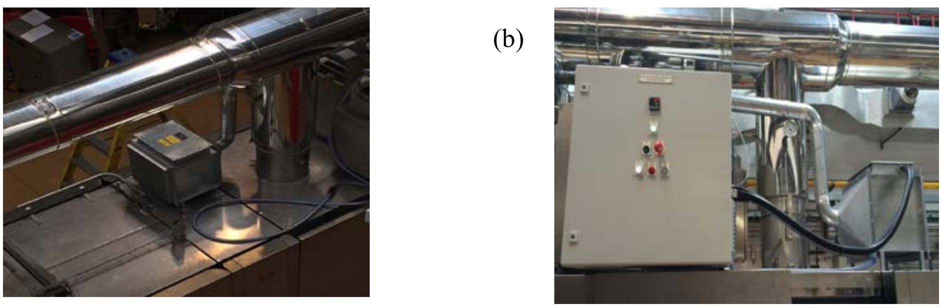


Fig. 2: (a) Electric resistance duct heater for preheating combustion air, (b) Control system for electric heater.

The design and selection of the resistance heater was based on the following information:

- Fuel (natural gas) consumption : 30 m^3/hr
- Primary air flow : 0.14 m^3/s

- Maximum temperature rise from ambient: 105° C
- Combustion air connection : 90 mm duct diameter

3. Results and discussions

3.1. Impact of Primary Air Temperature on Fuel Consumption

The baseline data was collected by running the oven at normal operating conditions, i.e. without preheating the primary air. Parameters such as primary air temperature and flowrate, fuel consumption, set point temperature, stack temperatures, exhaust composition and flow rate, wafer quality, amount of combustible gases (CO, CH_4 and H_2) in the exhaust were recorded. After collecting all baseline data, the electrical heating unit was turned on to gradually increase the primary air temperature to 105°C. A temperature difference of 10°C was maintained between the changes allowing sufficient time for the oven to stabilise before making further increment. The measurement of parameters mentioned above was repeated for the changed conditions. The chart shown in Figure 3 illustrates the impact of preheating the air supply on fuel consumption.

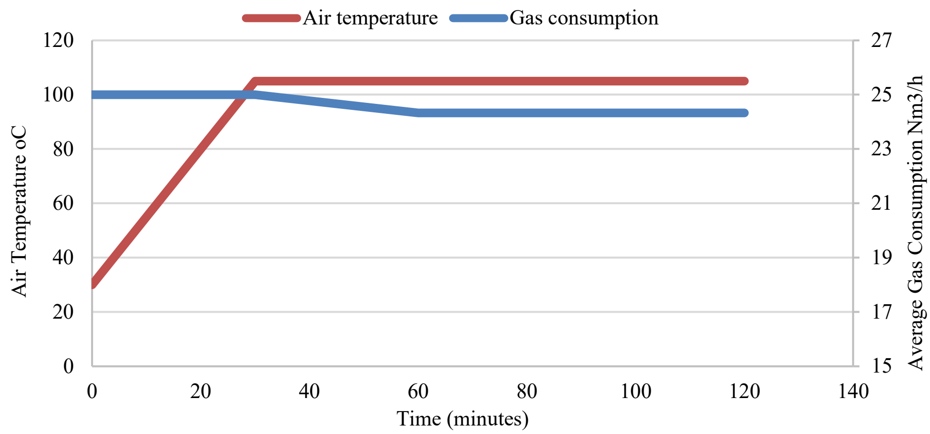


Fig. 3. Impact of primary air temperature on gas consumption.

Preheating primary air increases the flame temperature and hence also the plate temperatures. This triggers the valves in the fuel-air mixing device to reduce the fuel supply to maintain the plate temperatures at the set point temperature. A net saving of circa 4% in the average fuel consumption was observed during the preheating trails. Thus, indicating preheating primary air can result in significant fuel saving in wafer baking ovens.

3.2. Effect of primary air preheating on oven exhaust temperatures

The products of combustion, moisture released from the batter and secondary air used for cooling are released from the oven through three intermediate ducts located on top of the oven. The exhaust gases mix in the main exhaust manifold and are vented from the factory rooftop with the help of a centrifugal extractor fan. The schematic diagram of the oven shown in Figure 4 indicates the exhaust temperatures before and after preheating primary air. The exhaust gas temperatures in the intermediate ducts increased by 14-18°C whereas the overall (combined) exhaust temperature raised by 8°C. This increment in the exhaust temperature is advantageous for the heat transfer in the air-to-air heat exchanger as it gives higher heat transfer rates. The exhaust temperature levels were below the upper operating temperature limits of the extraction unit and therefore do not possess any safety issue for the baking process.

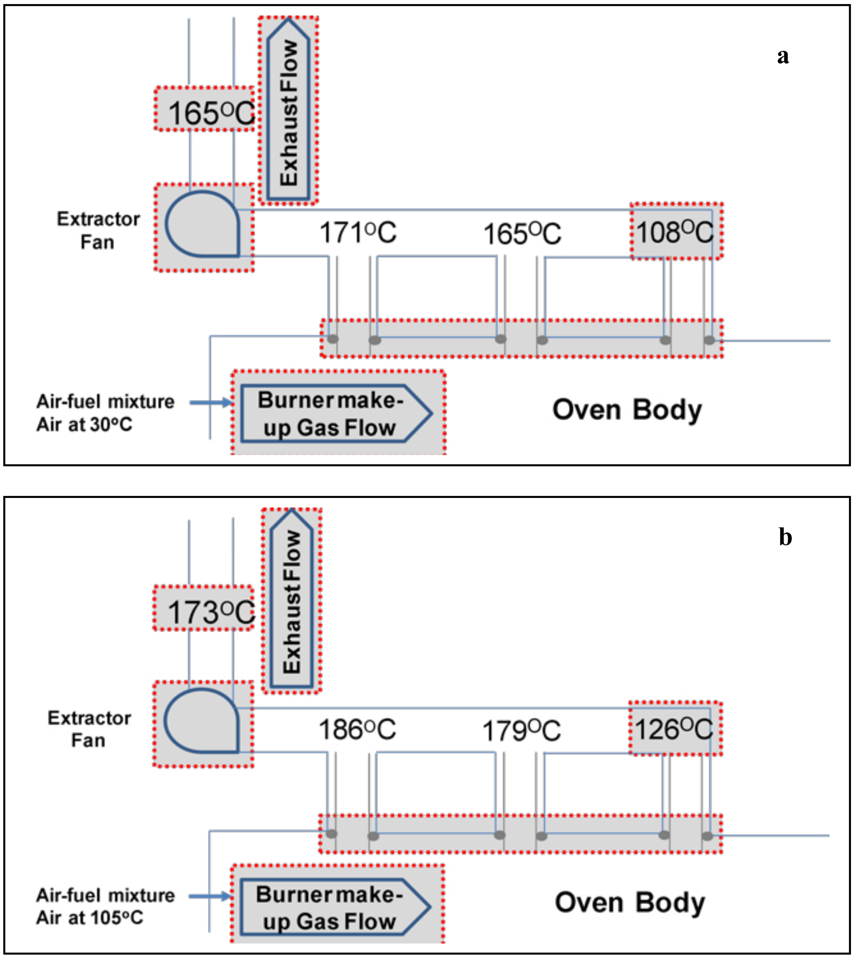


Fig. 4. Schematic diagram of the oven showing exhaust temperatures **(a)** before and **(b)** after primary air preheating.

3.3. Impact of primary air preheating on flame and product quality

The fuel supply device and burner nozzles are designed to yield an adiabatic flame temperature of 1,939°C for the mixture and a certain flame sharpness; bluish flame with a yellow tip. A yellow coloured flame indicates rich mixture whereas only blue colour flame indicates lean mixture of fuel-air. Preheating the primary air decreases the air density and thus the molar flow rate of oxygen for the same volume of air supplied. This can cause incomplete combustion of fuel which leads to higher fuel consumption to maintain the required flame temperature. To avoid any incomplete combustion, the flame quality was regularly monitored during the trials for any changes in the flame colour. No impact was observed on flame quality during the preheating experiments.

The wafer samples were collected during the trials for quality check. Moisture content, weight and thickness are the three key parameters that are used to evaluate the quality of a wafer sheet. A comparison of wafer quality at elevated primary air temperature with baseline figures is shown in Table 1. The table indicates that all three parameters used for quality check-up were maintained within acceptable range. This demonstrates that preheating primary air does not have any negative impact on the wafer quality.

Table 1.Wafer quality measurements before and after preheating trials.

Parameters		Baseline Measurement	Measurements after Preheating Primary Air
Moisture (mass %)	Maximum allowed	2.08	2.08
	Minimum allowed	1.73	1.61
	Average observed value	1.87	1.79
Weight (%)	Maximum deviation from required weight	3.86	3.76
	Minimum deviation from required weight	3.39	3.19
	Average deviation	3.61	3.47
Thickness (%)	Maximum deviation from required thickness	2.25	2.30
	Minimum deviation from required thickness	2.13	2.17
	Average deviation	2.20	2.23

3.4. Cost savings and environmental benefits of air preheating

The results obtained from the primary air preheating trials performed on the pilot oven were applied to an industrial scale baking oven used in a confectionary manufacturing plant to quantify the economic and environmental benefits of primary air preheating in real scenario. The industrial-scale oven used for this analysis is a scaled replica of the pilot baking oven used for the trials. Tables 2 and 3 show the key performance indicators and savings achieved by primary air preheating for an industrial scale baking oven, respectively.

Table 2.Key performance indicators of an industrial scale-baking oven.

S.No	Parameter	Units	Baseline measurements (w/o preheating)
1	Fuel/Gas consumption per hour	Nm^3	75
2	Gas density	kg/m^3	0.71
3	Calorific value of gas	kWh/m^3	11.0556
4	Per unit wholesale gas price (in pence) in UK	p/kWh	1.8
5	Load	kW	829
6	Operational hours per year	h	7000
7	Annual gas consumption	Nm^3	525,000
8	Annual energy consumption	kWh	5,804,190
9	Energy consumed per kg of wafer produced	kWh/kg	3.20
10	Exhaust temperature	°C	170
11	Exhasut flow rate	m^3/s	3.72
12	Potential heat available for recovery (sensible)	kW	138
13	Annual CO_2 emissions	tonnes	1,073

Table 3.Summary of heat recovery and savings from primary air preheating for an industrial scaled baking oven.

S.No	Parameter	Units	Measurements after preheating
1	Primary air flow	m^3/s	0.19
2	Primary air initial temperature	ºC	30
3	Primary air final temperature	ºC	105
4	Annual savings in gas consumption	Nm^3	21,000
5	Energy consumed per kg of wafer produced	kWh/kg	3.07
6	Annual energy savings	kWh	232,167
7	Annual cost savings	£	4,207
8	Annual CO_2 savings	tonnes	43

The industrial scale oven operates for 7,000 hours per year and consumes 525,000 Nm^3 of gas annually at normal operations i.e. without preheating. It uses 3.20 kWh of gas to produce 1 kg of wafer and emits 1,073 tonnes of CO_2 per annum. The preheating of primary air from 30 to 105ºC reduces the annual fuel consumption by 21,000 Nm^3 and generates savings of £4,079 per year based on a gas price of 1.8p/kWh. It also saves 43 tonnes of CO_2 from being emitted into the atmosphere per year. These industrial ovens have a lifetime of 30 years indicating 1,288 tonnes of CO_2 and 630,000 Nm^3 of fuel savings for the oven's lifespan. The electric resistance heater could pre-heat the primary air only up to 105ºC. In the actual heat recovery system design, this temperature will be much higher (around 150ºC), depending upon the exhaust temperature, thus further improving the overall benefits of the heat recovery system. The primary air preheating uses only 11-15% of the total heat available for recovery. Large confectionary manufacturing plants contain more than one baking oven which indicates that the heat available in the exhaust from one baking oven can be used to pre-heat the primary air of several ovens, thus giving more benefits in terms of cost, fuel and CO_2 savings.

4. Conclusion

The preheating trials were considered a success, delivering clear indication that increasing the temperature of the primary air supply to 105ºC in a controlled way can deliver 4% reduction in fuel consumption, saves £4,207 of running cost and avoids 43 tonnes of CO_2 emissions per annum. In the actual design of the heat recovery system, the primary air temperature would be close to 150ºC thus, providing more savings in fuel consumption and running costs. Importantly, the evidence collected from wafer quality checks during the experiments indicated no negative impact on product due to primary air preheating.

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