Measuring oven exhaust gases during bread baking

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Summary

Gas flow rates were measured from bread and cake during baking to demonstrate that the volume of gases released from products varied along the length of a travelling oven. Measurement and calculation techniques accounted for the main gases, carbon dioxide, air, ethanol and steam. Rates of gas released from the products increased with baking time and were highest towards the end of the oven. Steam made the major contribution. Knowing the gas flow rates is important for controlling the flue gas extraction rates from the flues along a travelling oven. By balancing the inlet and outlet gas flows in an oven it is possible to improve oven combustion and save energy.

Energy savings of 4.7% were estimated through improved control of flue gases by linking this to the gas burner fire rate. This enabled unbalanced flow rates in the flue to be limited, which reduced oven cooling at times of low burner fire. This has relevance to product changeovers, where a space is left between products and to periods of low throughput. Payback periods varied from 1 to 5 years depending on the burner and controller technology fitted to an oven.

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INTRODUCTION

The work reported here provided background data that will be useful for optimising gas flow rates in and out of a travelling oven. It addressed the issue of flue gas removal that is currently achieved with fixed speed fans in each flue of a travelling oven. One of the unknown factors in an oven gas balance is the volume of gases released from the products as they travel along the conveyor belt. These gases will leave the oven in an adjacent flue.

It is common for a large bakery oven to be fitted with 3 – 6 flues of equal diameter and with the same fan specification for each flue. However, the volumes of gases leaving each flue of a travelling oven are unlikely to be constant over the oven length and also will vary with changing oven load. The theory was that fixed speed fans do not allow for fine tuning the oven combustion air because of the constant pressure differentials created. This results in reduced combustion efficiency caused by sub-optimal fuel to air ratios, and excess air drawn into the oven can cool the equipment surfaces.

Oven efficiency

This work was part of a collaborative project funded by Campden BRI and the Regional Growth Fund, with support and advice from The Carbon Trust (Feb 2012 to Feb 2014). The project aims were to balance the gases entering and leaving a travelling oven (see Figure 1) so that air flow for combustion can be linked with the volume of gases that exit in the flues. This is important because the constant speed flue gas fans need to draw a flow into the oven from the bakery at all times. This is a legal health and safety requirement to ensure that operatives do not get exposed to combustion gases such as carbon monoxide. However, with fixed speed fans, during periods of low combustion, air flow from the bakery is likely to be excessive, which can cool the oven surfaces and reduce its efficiency. The question being addressed here was how to measure or calculate the volume of gas that leaves the oven through each oven flue.
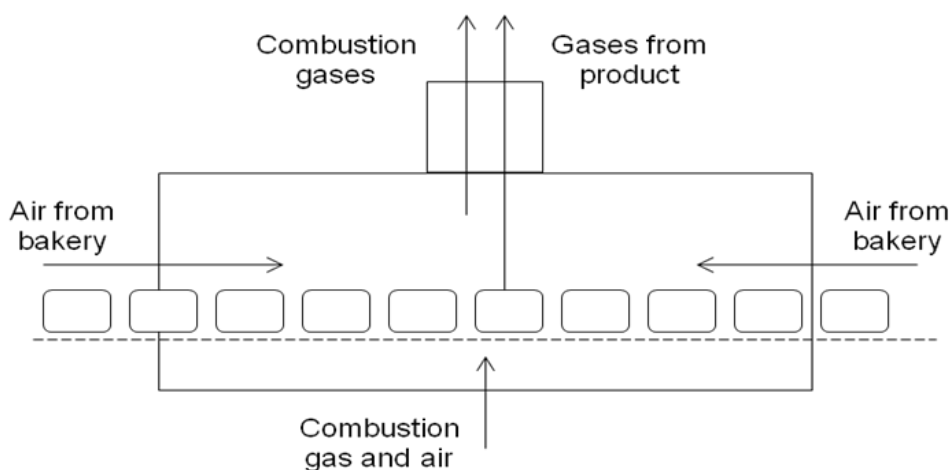

Figure 1: Gases entering and leaving a travelling oven

Bakery production

Bread production in the UK is dominated by the high volume plant bakeries, which are responsible for about 80% of bread consumed in the UK (Federation of Bakers figures, www.bakersfederation.org.uk). Plant bakery ovens are responsible for most of the energy demands in the bakery. Refrigeration and air conditioning also contribute to high energy demands, although most bakeries use ambient air for cooling. Therefore, the most obvious way to reduce energy is to focus attention on the oven step.

High speed bread bakery lines are often running at 8-10,000 units per hour. The highest sales volume product in the UK is the 800 g lidded loaf. Baking times for 800 g tinned bread vary from 18 to 24 minutes in continuous or travelling ovens depending on oven type and whether the bread is lidded or unlidded. These ovens are lengthy pieces of equipment that usually have between three and six flues along their length. Each flue has a fixed speed fan together with a physical restriction plate, often known as a damper, which allows adjustment of the flue cross-sectional area.

Energy savings made on plant bakery ovens will be significant because of the high energy usage in baking. Data from the Carbon Trust (2010) suggested a median figure for energy cost for a plant bakery oven of £335k per annum. Figure 2 presents the breakdown of oven energy use for a typical direct-fired gas oven showing that hot air exiting the flues is responsible for around 20% of gas use. This lost energy makes no contribution to heating up bread dough and is a direct loss. The theory for this work was that gas flow rates in the flues affected the oven efficiency and so there was potential to improve oven efficiency by controlling flue gas flow rates with variable speed fans (VSD's).
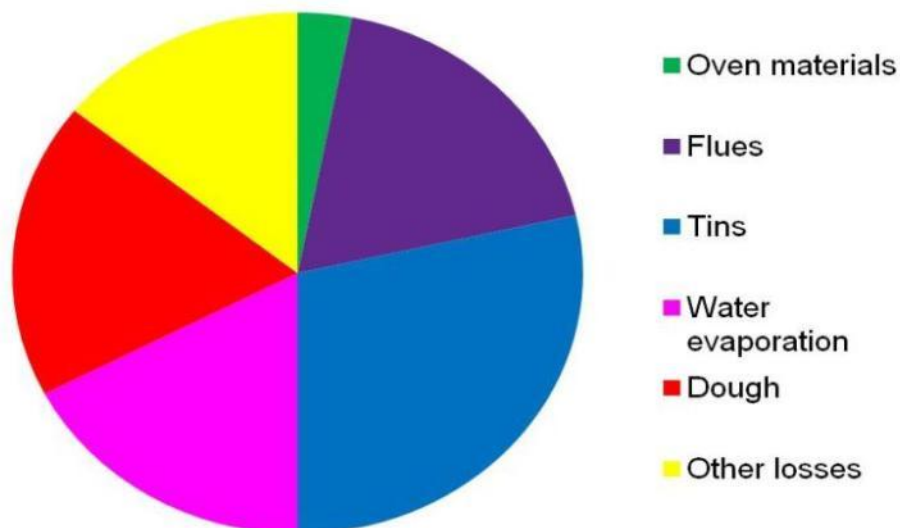

Figure 2: Breakdown of oven energy use for a direct-fired gas oven

Gases released during baking

Previous work on gas release during the baking of products is sparse. There are many publications on carbon dioxide generated during proving because of the need to retain carbon dioxide within dough gas cells. These focus on mixing regimes to create fine gas cells or on the emulsification systems that keep the gases within a fine network of cells. Very few publications have continued this into baking, even though retention of intact gas cells is critical during the early stages of baking where emulsifier properties are challenged by higher temperatures and increased gas cell pressure.

One of the first pieces of relevant baking work was done by Daniels and Fisher (1976) when they investigated the beneficial effects of fat on gas retention. Carbon dioxide (CO_2) was their gas of interest. They collected CO_2 by bubbling it through sodium hydroxide solution and measured the molar concentration with a burette. This gave the increase in CO_2 as the baking time increased. Figures 3a and 3b illustrate their data as mmol CO_2 generated from a 400g open top white loaf (Figure 3a) and converted to litres of CO_2 at the baking temperature of 215°C (Figure 3b). Conversion from mmol to litres assumed CO_2 was an ideal gas, an assumption that was sufficiently accurate for these calculations.
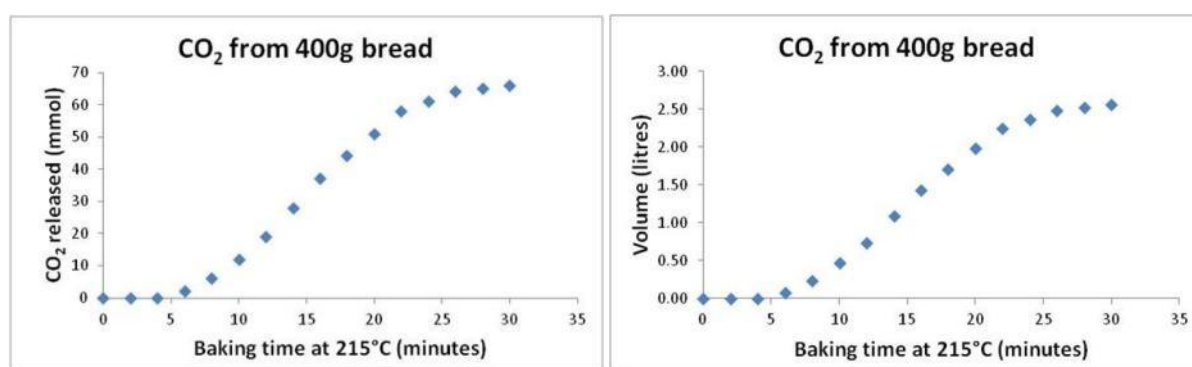
Figure 3: CO_2 measured by bubbling gases through sodium hydroxide solution, during baking a 400g open top white loaf (redrawn from data of Daniels and Fisher, 1976). 3a is in mmol and 3b converted to litres.

A similar piece of work to that of Daniels and Fisher (1976) was by Moore and Hoseney (1985) who discussed the leavening of bread dough, but made suggestions about dough expansion during baking. They calculated the CO_2 volume from expansion of the gas bubbles together with CO_2 released from the aqueous phase as the dough increased in temperature. They concluded that CO_2 alone did not explain the increase in volume from dough to bread during baking. Ethanol was significant, particularly at around 70°C when its vaporisation rate increased rapidly.

A further publication of interest was by Bloksma (1990) who compared the Moore and Hoseney (1985) calculations with his own on partial pressures of gases during baking. Bloksma included CO_2, ethanol and water in his own calculations of thermal expansion. He concluded that water (steam) contributed more than half of the oven spring volume, with ethanol and CO_2 responsible for much of the rest. These calculations were done up to 70°C because this was the stage when Bloksma considered the oven spring ended and further volume increase was negligible. Bloksma (1990) estimated substantial differences in the quantities of each gas as well as in the total volume generated compared with Moore and Hoseney (1985).

The objective of this work was to control the oven gas combustion by balancing inlet and outlet gases. Therefore it was necessary to know gas volumes produced as baking time progressed. This required knowledge of which gases were produced, when they were produced and in what quantity.

During bread baking there are several gases that contribute to the gases that exit the oven through the flues. The main gases are described in Table 1.

Table 1: Gases released from bread during baking

Gas	Comment
Carbon dioxide	Generated by yeast during aerobic and anaerobic fermentation of glucose. Anaerobic fermentation is the dominant effect.
Ethanol	Generated by yeast during anaerobic fermentation of glucose. Molar quantities of ethanol are the same as for carbon dioxide during anaerobic fermentation. Ethanol boils at 78.4°C (www.engineeringtoolbox.com) and so its influence on dough expansion is significant as the dough temperature approaches 70°C.
Water	Approximately 50 g is lost from a 900 g dough piece (800 g unlidded loaf) during baking. Much of this will be water which will turn to steam.
Air	Air contributes to flue gas volume in a number of ways. Nitrogen left in the bubbles will increase in volume as it increases in temperature. Dissolved gases (oxygen and nitrogen) will come out of solution as the dough liquid increases in temperature. The tin/bread volume will displace an equal volume of air as it enters the oven.
Other volatiles	A number of volatile molecules are generated from fermentation, such as carboxylic acids, aldehydes, ketones and alcohols. These will contribute to gas volume.

Carbon dioxide

This is the gas that is commonly assumed to be responsible for inflating dough during proof and baking. However, it is only partially responsible for the volume increase. Carbon dioxide generation takes place during two stages of fermentation.

Yeast first metabolises oxygen in the air bubbles that are introduced to dough during mixing (see Equation 1). Yeast has the ability to metabolise both aerobically and anaerobically, but aerobic fermentation represents an easier metabolic pathway for the yeast. Aerobic fermentation is the first pathway and will continue until all of the oxygen is used up and the conditions in the dough become anaerobic.

$$C_6H_{12}O_6 \quad + \quad 6O_2 \quad \rightarrow \quad 6CO_2 + \quad 6H_2O \qquad\qquad \text{Equation 1}$$

The quantity of air entrained during dough mixing will dictate how much CO_2 can be generated in the aerobic phase. Spiral mixers are very effective at folding air into dough and can entrain up to 13% air by volume (Millar and Tucker, 2012). A Tweedy mixer, as used in the Chorleywood Bread Process (CBP), operates in a closed system and therefore entrains less air unless it is operated using pressure or by operating the mixer under partial vacuum with the vent valve open. The primary reason for forcing air into the dough is to help oxidise the gluten so that the gas cells have improved gas holding ability. Air content in dough up to 16% can be achieved with a full pressure-vacuum system.

Volumes of carbon dioxide produced during the aerobic phase can be calculated from Equation 1 and by making a number of assumptions. One of these is that both oxygen and carbon dioxide are ideal gases, and so one molar volume of oxygen in Equation 1 produces one molar volume of carbon dioxide. Water is the other fermentation product, which is produced in liquid form and acts to soften the dough.

Equation 1 can be used to calculate the mass of glucose used in the aerobic stage of fermentation. This assumes the yeast uses up all of the oxygen in the bubbles, leaving only nitrogen. Much of the carbon dioxide produced from the fermentation dissolves into the aqueous phase that surrounds the gas cells. It will be released as gas during the baking process as the dough temperature increases. The assumptions and stages in these calculations are given in Appendix 1 for a 453 g dough mass. The calculated volume of CO_2 produced during the aerobic stage is 0.0000017 m^3 or 0.017 litres.

Having used the available oxygen, subsequent fermentation during proof will take place with the dough in an anaerobic condition. Yeast will obtain the oxygen needed directly from the glucose, according to Equation 2.

$$C_6H_{12}O_6 \quad \rightarrow \quad 2CO_2 \quad + \quad 2C_2H_5OH \qquad\qquad \text{Equation 2}$$

As mentioned earlier, Daniels and Fisher (1976) made measurements of CO_2 generation during baking of a 453 g dough mass. The cumulative amount of CO_2 released was 65 mmol, which equated to a volume of 2.5 litres at a flue gas temperature of 200°C. Conversion of the gas volumes to a typical flue temperature of 200°C assumed it was an ideal gas.

Ethanol

Equation 2 shows that ethanol and carbon dioxide are produced in equal molar quantities during anaerobic fermentation. Ethanol boils at 78.4°C and so it is a reasonable assumption that all of the ethanol is evaporated during baking and must pass out through the oven flues. Ethanol is, like carbon dioxide, close to being an ideal gas. Hence, for the 453 g dough piece, it will occupy a similar volume to that of carbon dioxide (2.5 litres at 200°C) and so the total volume for both gases will be 5.0 litres at 200°C.

Ethanol will evaporate during the oven process over a period of time, but it is likely to be gone from the bread soon after its boiling point of 78.4°C is reached. The rate of ethanol evaporation is likely to be at its highest when the internal core temperature is above 70°C. Figure 4 is a time-temperature plot of bread core temperature taken by placing a remote logger (Signaloger) inside a 450 g dough piece. A core temperature of 78.4°C was reached after 20 minutes at 200°C. It is expected that all of the ethanol will have evaporated by this time. Core temperature change is rapid between 15 and 22 minutes, which is the period when the ethanol evaporation rate is highest.
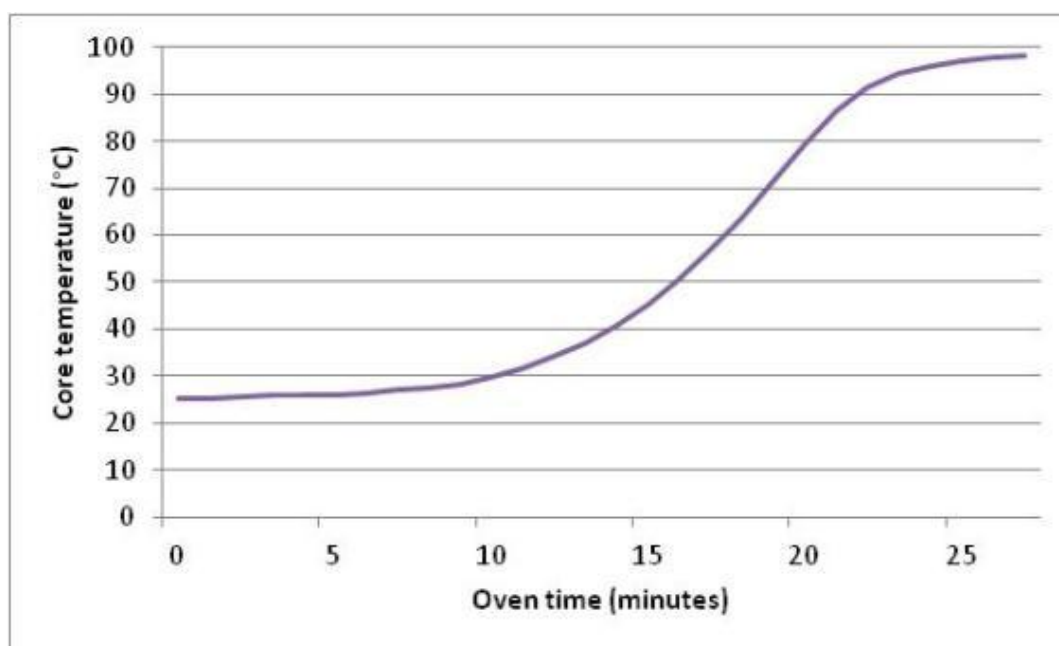

Figure 4: Core temperature increase during baking a 400 g loaf in a vacuum oven at 200°C. Bake time was 25 minutes.

The role of ethanol in dough behaviour is complex and warrants further investigation. For example, ethanol increases the solubility of carbon dioxide (Dalmolin *et al.*, 2006) so that more can remain in solution and contribute to increased oven spring. Ethanol also increases the solubility of the gliadin wheat protein fractions. This may have an impact on the rheological behaviour of dough because the gliadins are thought to confer extensibility to dough.

Water (steam)

Water boils at 100°C and so will be released later into the baking process than ethanol (78.4°C) or carbon dioxide (-56.6°C). It is likely that the structure of a baked product will have set by the time water evaporation occurs at a significant level and so the contribution of steam to bread volume increase may not be as significant as for carbon dioxide or ethanol. However, water vapour will be more important than the other two gases for its contribution to the gas volume that exits the oven through the flues.

Typically, the weight of an 800 g lidded loaf decreases by 40 to 50 g during baking, and similarly a 400 g loaf loses around 25-35 g. These values are approximations and vary depending on recipe, process and desired crust strength. An 800 g loaf will be scaled at around 900 to 915 g and a 400 g loaf at 450 to 465 g. Much of the water will be generated towards the later stages of baking as the product temperature reaches 100°C in the outer parts of the product. There will be an evaporation front that moves towards the product core but there will not be much water evaporated from the core because the temperature does not reach 100°C. It is common that the core moisture levels of dough and bread are similar.

Calculations presented in Appendix 2 demonstrate that a 400 g loaf loses approximately 6 g of fermented carbohydrates during proof and baking. The remaining 19-29 g weight loss is water. Assuming ideal gases, the volume occupied by 19 g of water is 41 litres at a flue gas temperature of 200°C, which compares with 2.5 litres for CO_2 and 2.5 litres for ethanol (see Table 1).

Air

The volume of air that ends up in the flues is more complex than it first appears. By air we are referring to its component gases, oxygen and nitrogen. Oxygen is used up by the yeast during its aerobic phase and so will be replaced in the gas cells by carbon dioxide once the liquid surrounding the gas cells is saturated. At a proof temperature of 38°C, carbon dioxide is soluble in water to a level of 1.0 g/kg and partially soluble in oil. Nitrogen is left in the air bubbles and will be unaffected by the yeast during the proof. However, it will expand as the bread temperature rises.

Towards the end of the oven process the gas cells contain nitrogen together with other gases generated during fermentation and baking. Therefore, each gas cell is a mixture of nitrogen and water vapour, together with small quantities of carbon dioxide, ethanol and low molecular weight organic compounds that vaporise easily. There is a gas exchange that takes place close to the oven exit as cell walls dry out, lose their flexibility and break. This is observed as a bread volume reduction and must result in some gases being released to the flue. However, it is a small percentage of the bread volume and so gas volumes released to the flue will not change to a significant extent.

To calculate the relative significance of air compared with the other gases data is used for the volume of air entrained during mixing. The volume of gas (air) in a 453 g dough piece is approximately 0.08 litres (see Appendix 1 for air calculations in a 453 g dough piece), which equates to 0.15 litres at a flue gas temperature of 200°C. This is a low amount compared with steam, ethanol and carbon dioxide, and so inaccuracy in the calculation does not impact on the calculated flue gas volumes.

Table 1: Estimated volumes of gases released from bread dough during the baking process for a 400 g loaf (scaled at 453 g). Data is for the oven stage only.

Gas	Volume at 200°C (litres)	% contribution
Carbon dioxide	2.5	5.4
Ethanol	2.5	5.4
Water (steam)	41.0 *	88.7
Air	0.2	0.5
Total	**46.2**	**100.0**

* Volumes in Table 1 are estimated from literature data. Water evaporated during baking assumed a 25 g weight loss (conservative), of which 6 g was fermentable carbohydrate. These data were calculated from Daniels and Fisher (1976) together with measurements of loaf weight loss from baking experiments at Campden BRI. They illustrate the significant contribution of steam to gas volumes exiting the oven flues.

The time during baking when gases in Table 1 are released is of relevance to oven spring with yeast-leavened products as well as improved control of oven combustion through flue gas management. Carbon dioxide has the lowest boiling point (-56.6°C) so is released first, followed by ethanol (78.4°C) and finally water (100°C). It is clear from Table 1 that steam is the most important gas in terms of its volume contribution to flue gases.

Objectives of the work

The objectives were to develop methods to measure the volume of gases released from bread and cake during the oven process, together with the flow rates as a function of baking time. The purpose was to generate data that contribute to the volume balance for gases entering and exiting a travelling oven. This was required so that inlet combustion air and outlet flue gas removal can be optimised with the result that oven efficiency can be improved. This has particular relevance to periods of low combustion during which excessive air flow cools the oven surfaces and reduces efficiency. Parallel work at Spooner Industries was linked with this project and is reported later.

Previous work, such as Daniels and Fisher (1976) and Moore and Hoseney (1985), worked on 400 g tinned white bread. Baking trials reported here also used 400 g loaves, partly to allow comparison with this work but also because of space limitations in the vacuum oven. Analysis of data for gas evolution from 400 g bread is scaled to 800 g so that its relevance to industrial bakeries can be compared.

MATERIALS AND METHODS

As discussed earlier, measurement of the volume of gases released from baked products during the oven process has not been studied to the same extent as with proving. Our interests were in measuring gas generation from the product as it moves along the oven belt. These values can be compared with combustion gas volumes so that the total volumetric flow rate is known. However, the technologies for directly measuring gas volume or flow rate at flue gas temperatures of 180-200°C do not exist. It is possible to make flow rate estimations using pressure or velocity measurements in the flue, which are then converted to flow rate based on the flue cross-sectional area. These calculations are unreliable because assumptions must be made about the compressibility of air, its variable water content, and density at very high temperature in the flues. Also, there is the added complexity in taking a measurement that does not interfere with the result. Pressure measurements (using pitot tubes) are easier to use than velocity measurements (using anemometers) because of the hostile conditions of a bakery flue. Since pressure is directly proportional to the square of velocity it is possible to estimate the proportionality factor that applies to a single flue system. This allows estimations to be made for the flue system being considered and this measurement method works for an industrial bakery where spot checks are required. It is unlikely to provide a method that will enable flow rate to be estimated as baking time progresses.

Our approach was to measure a combination of condensable and non-condensable gases based loosely on the methods of Daniels and Fisher (1976). One of the first challenges was to find an oven suitable for measuring gases generated from the product but without the complication of having to measure air flow into the oven or gases leaving the oven through leaks in door seals. This was solved by using a laboratory vacuum oven that had excellent door seals together with an entry port that could be sealed off and exit port for measuring gas flow. Heat transfer within the oven did not replicate a bakery oven but the accuracy in controlling gas flows in and out was considered to be more important.

Measurement of non-condensable gas flow rates during baking

The volume of gas produced from various products was measured by baking at 200°C in a vacuum oven (Gallenkamp). A one way valve was fitted to the inlet port and a thermal dispersion mass flow meter (Hewlett Packard) to the outlet (Figure 5). Water vapour and ethanol from the products was condensed by causing the gas to flow through a U-tube chilled with ice water. Hence gases responsible for the flow rate changes were mostly carbon dioxide and air.

Flow rates of gases from each test in the vacuum oven were recorded manually from flow meter readings every minute during baking. Products studied included yeast leavened bread, and various chemically leavened cakes, muffins and scones. The reason for studying different leavening systems was to determine if the flow rate change with baking time followed a different relationship. Appendix 3 gives the recipes for each product baked (Tables A1 to A6) and Appendix 4 gives graphs for gas flow rate every minute during baking (Figures A1 to A9). Gas flow rate was measured in standard cubic centimetres per minute (sccm).
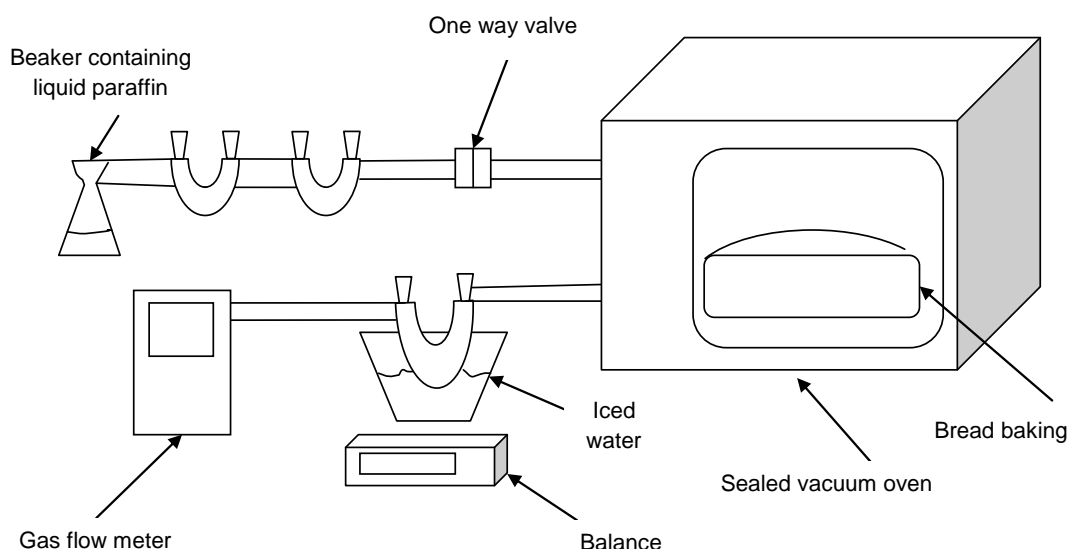
Figure 5: Schematic diagram to measure the volume of gas produced during baking

Measurement of all gases given off during baking

It is clear from calculations presented earlier that carbon dioxide and air contributed less than 10% of the total gas flow rate (see Table 1). If the assumption of equal volumes of carbon dioxide and ethanol is approximately correct during the dominant anaerobic fermentation phase, steam contributes around 95% of gas volume released from bread during baking. This is a substantial amount and sufficiently large that engineering calculations on gas flow optimisation can ignore the contribution of all gases other than steam.

On this basis a baking trial was set up to measure weight loss during baking and to generate a plot of gas volume against baking time. These data were calculated by removing 400 g loaves at 2 minute intervals during baking. A larger oven was required than the laboratory vacuum oven. The oven was a direct gas-fired reel oven with six shelves and standard baking time for 400 g loaves of 24 minutes at 240°C. This type of oven has a major advantage over almost all other oven types for removing samples before the baking is completed. This is because the door opening is small compared with the oven size, which results in minimal heat loss from the oven during sample removal. Loaves in their tins were weighed immediately on removal from the oven to determine the weight loss as the bake progressed.

Conversion of weight loss to gas volume assumed that all weight loss was water, which again was a fair engineering assumption, and that steam behaved as an ideal gas. For an ideal gas at STP (273K and 1 atmosphere pressure) 1 mole occupies 22.4 litres or 0.0224 m^3. Gas volumes were calculated for 200°C flue temperatures using the ideal gas law (see Equation 3):

$$PV = nRT$$

<div style="text-align: right">Equation 3</div>

Where,   P is the pressure of the gas (Pa),
            V is the volume of the gas (m^3),
            n is the number of moles, in this case of water,
            R is the ideal, or universal, gas constant (R has the value 8.314 $J.K^{-1}.mol^{-1}$),
            T is the temperature of the gas (K).

RESULTS AND DISCUSSION

Non-condensable gas flow rates during baking

The figures in Appendix 4 show the change in gas flow rate during baking of a range of products. The data for 2 x 400 g loaves of bread is replicated here because this is relevant to the main theories of gas flow optimisation (see Figure 6). Other figures provide useful information to the differences between products and between yeast-leavened and chemically-leavened products. Note that carbon dioxide is the main gas that contributes to the flow rate in these figures, with most of the ethanol and water already condensed in the U-tube.

On first inspection of Figure 6 it would seem that there are differences between the three replicate trials. However, measurements with a flow meter are difficult to implement under these conditions and the conclusion is that these are a true reflection of the gas flow rates during baking. Each of the three plots shows a similar pattern, reaching a maximum flow rate between 15 and 20 minutes into baking, which reduces towards the end of baking time.
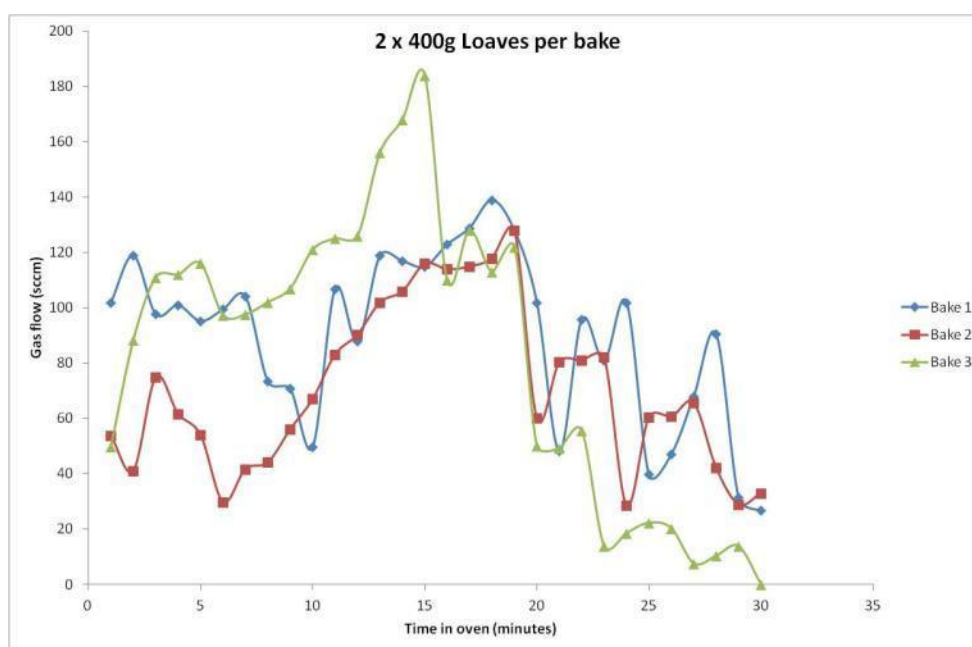

Figure 6: Gas flow measured with a flow meter during baking of 2 x 400g white open top loaves, in a vacuum oven at 200°C, showing 3 replicate bakes

Analysis later in this report has converted these flow rates to gas volumes at a typical flue temperature of 200°C. The aim here was to use the flow meter to generate data similar to that of Daniels and Fisher (1976) and Moore and Hoseney (1980). Figure 7 presents the flow rate data as an average for the three replicate trials (note that Figure 7 presents data for two loaves of bread). This showed that the flow meter method measured a cumulative total of 2.04 litres of gas per loaf, which compared with 2.56 litres from Daniels and Fisher (1976). Both volumes are corrected for 200°C. A number of areas for improvement of the flow meter method are suggested to increase accuracy:

- It is likely that the gas temperature through the flow meter increased during the baking time as the temperature of the water used to condense ethanol and water increased. This will change the current used in the anemometer.
- Not all of the condensable gases will collect in the water trap.
- Air leaks may be present in the connectors.
- Some carbon dioxide will dissolve in the water trap.

However, the volume totals were of the same magnitude and therefore suggest that the flow meter technique provided data that can be replied upon for further analysis.
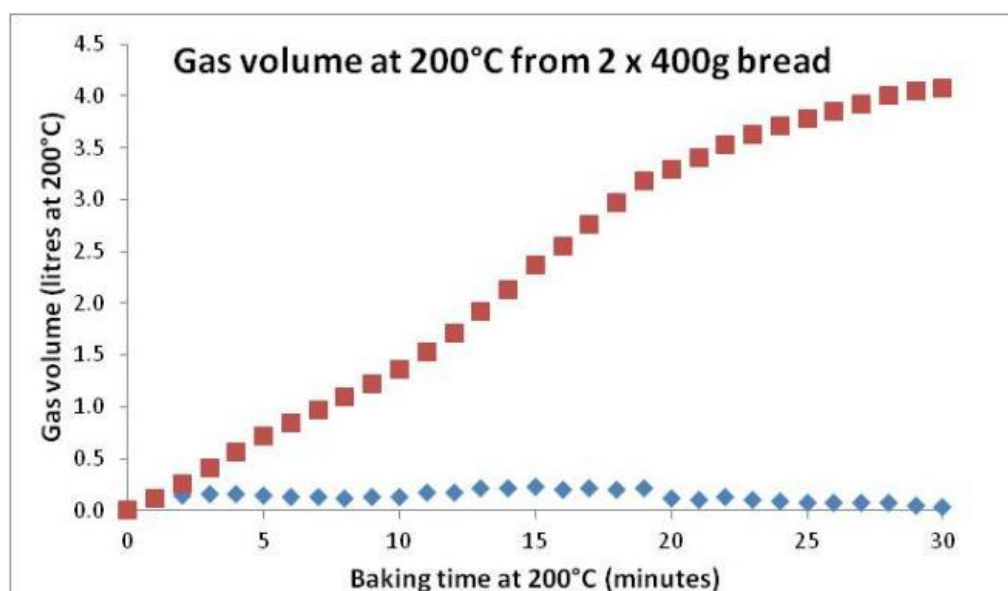

Figure 7: Mean cumulative gas flow rates (from Figure 6) during baking of 2 x 400g white open top loaves, in a vacuum oven at 200°C. Actual mean flow rate data is shown by blue diamonds.

Volumes of all gases given off during baking

Table 1 showed that water converted to steam during baking had the greatest impact on total or cumulative gas volumes released from the products. This project had objectives to optimise flue gas control; therefore, the interests were the changes in steam volume rate as bread changed from a 36-38°C dough to a 96-100°C baked loaf. Measurements of loaf weight every 2 minutes of baking at 240°C in a direct gas-fired oven were taken. Figure 8 presents the cumulative weight loss for each loaf removed.
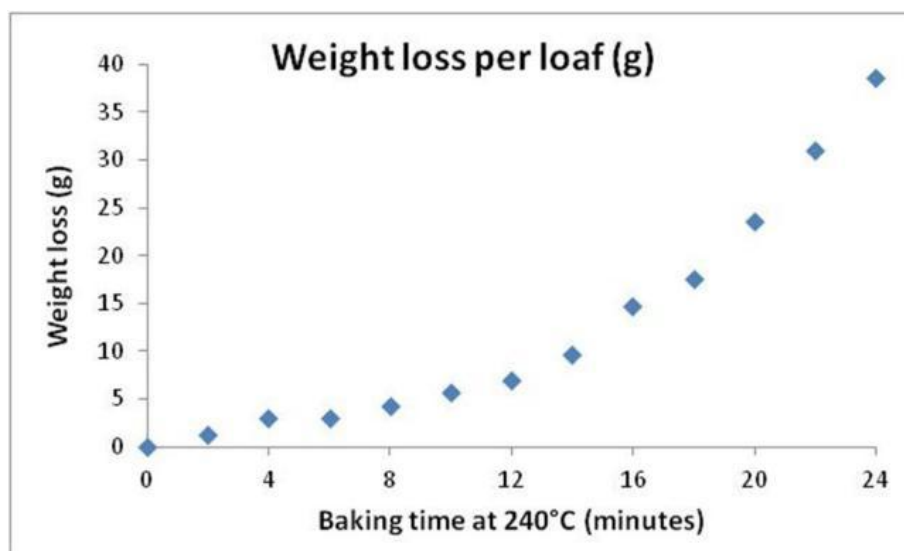
Figure 8: Weight loss during baking of a 400g open top loaf. Much of this is water (steam) that contributes to flue gas volume.

Of interest to improved flue gas control is the relative volumetric rate of gas released from the bread compared with that from the combustion products. These calculations assumed a typical industrial bread oven operating at 8,000 units per hour, with three burner zones, each of which has a separate flue. Figure 9 presents the relative gas volumes that exit the flues (as percentages of the total volume) as the bread moves from the oven inlet to the outlet. Table 1 showed calculations for absolute gas volumes, arriving at 46.2 litres per 400 g loaf. As expected from the weight changes in Figure 8 the increase in flue gas volumes is exponential.
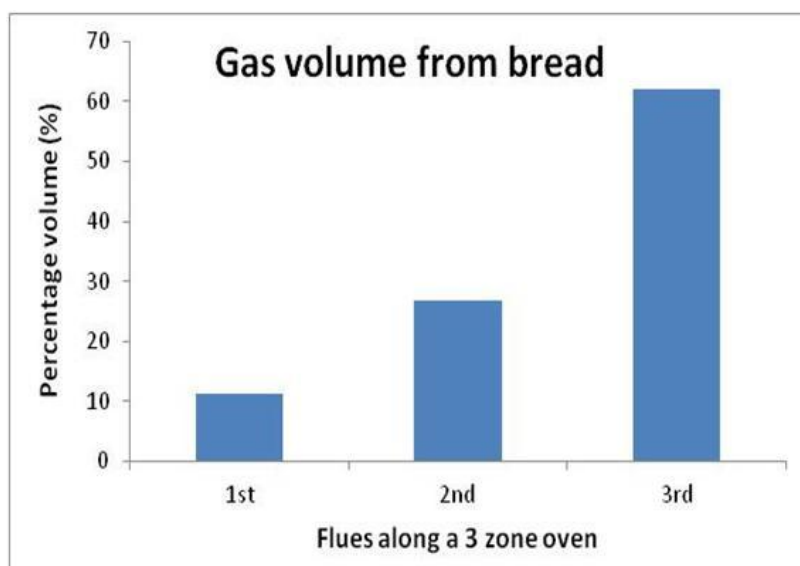

Figure 9: Estimated percentage of flue gas volume from measurements of weight loss during baking of a 400g open top loaf (data in Figure 8)

Calculated combustion gas volumes during baking

One source of data that was useful for this oven optimisation work was the Carbon Trust report (CTG084). A representative sample of UK bakery ovens was surveyed in this report so that carbon dioxide emissions could be calculated from bakery combustion gases. These data contained calculations that provided a basis from which total combustion gas volumes were estimated. Table 2 presents the data used to calculate combustion gases released when baking a 400 g loaf. The key information is the value of 43.4 litres for every 400 g loaf. This is a significant amount of gas because it is similar in volume to that calculated from the baked product (46.2 litres).

Table 2: Volume of combustion products from gas burnt to bake a 400 g loaf

Baked loaf weight	400 g
Energy to bake loaf	0.0884 kWh *
CO_2 released from combustion gases per loaf	16.4 g **
	8.4 litres at STP
	14.5 litres at 200°C
H_2O released per loaf	29.0 litres at 200°C ***
Total combustion gases to bake 400g loaf	**43.4 litres at 200°C**

* Oven energy consumption is 221 kWh / t product with direct gas ovens, mean figure for large bakery.
** Carbon dioxide released per kWh is 0.000186 t CO_2 (2010 Carbon Trust report CTG034).
*** $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Tables 1 and 2 highlight the volume of gases released from products during baking (Table 1) and from combustion products (Table 2). The overall gas volumes from product and combustion are similar. It is likely that the calculation and measurements systems used to obtain these values contain assumptions. However, the significant outcome is that they are sufficiently similar so that optimisation of gas flows in ovens should consider both sources. Figure 10 serves to illustrate the similarity in gas volume.
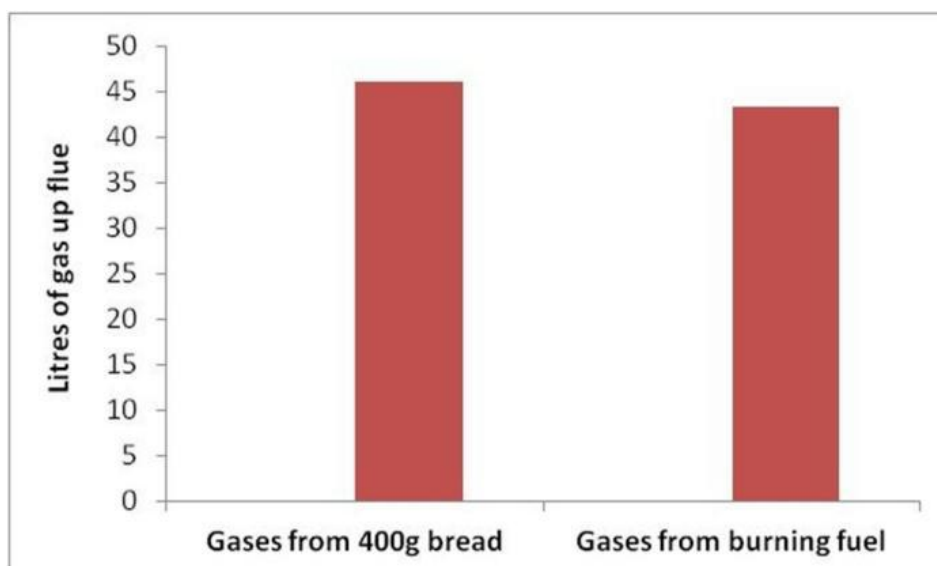
Figure 10: Gas volumes from bread and from combustion products to bake a 400 g loaf, illustrating that they are similar in magnitude

Having established that volumes of gas from baking bread and burning combustion fuel are similar, it is interesting to know how they change over the oven length. Figure 9 presented these data for gases released from baking bread, showing an increase as the bread moves towards the oven exit. To calculate these changes for combustion gases, data were obtained from Spooner Industries for a typical three-zone bread oven. These data were the burner fire rates in kWh. In order to compare with Figure 9 these are presented as percentages of the total, as given in Figure 11.
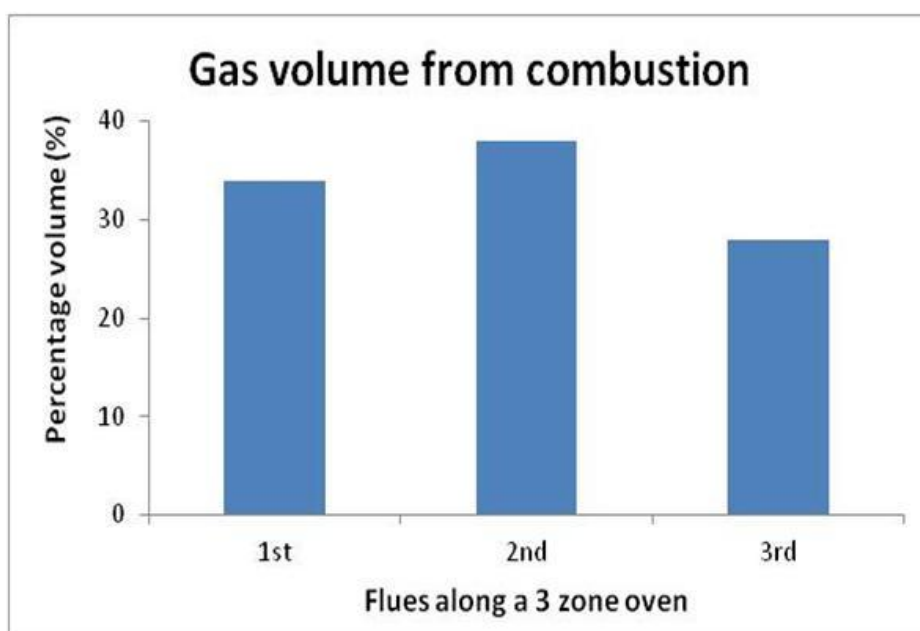

Figure 11: Relative percentage of flue gas volume from combustion products, calculated from burner fire rate data provided by Spooner for a commercial 3-zone bread oven

It is clear that the gas volumes from bread baking are not evenly distributed, as shown in Figure 9, but they are reasonably even from the combustion products, as shown in Figure 11. The latter may seem strange because the evaporation rate of water increases almost exponentially towards the oven exit as the bread temperatures rise towards 100°C in the outer regions of the bread. Evaporation involves a phase change that is high in its energy demand. However, the first zone of a bread oven heats relatively cold tins and dough from 36-38°C, which also demands a high amount of energy. The middle zone of the oven also delivers high rates of energy into the part-heated tins and bread, as well as starting the water evaporation process. Temperatures in the middle zone are usually higher than in the first or last zones, which requires a higher rate of burner fire to achieve. Figure 12 presents both sets of gas volume data on one bar chart.
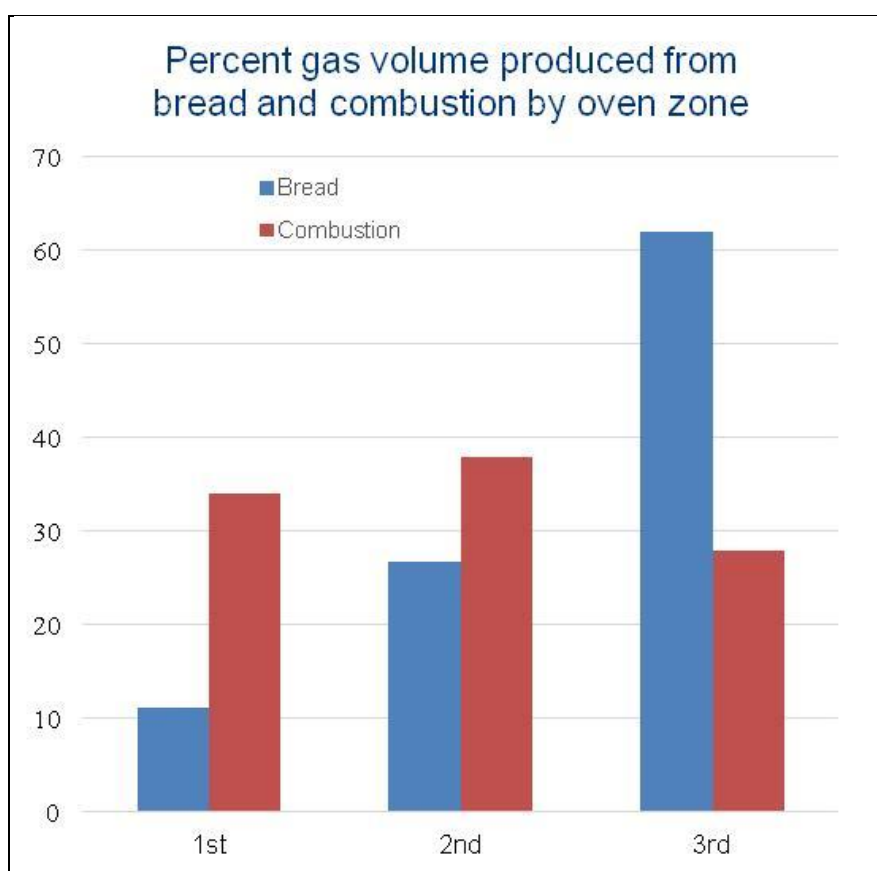

Figure 12: Relative percentage of flue gas volume released from bread and combustion products for a 3-zone bread oven

Significance of the research

Flue extraction fans in many industrial ovens are usually installed with fixed speed motors, with manual dampers controlling the proportion of flue cross-sectional area available for flow. This is not an ideal set-up to optimise gas flows leaving the oven. One of the challenges for this project was to estimate the gas volumes generated by bakery products during baking and how these gases might impact on oven efficiency. By linking the flow rate of flue gases from the bakery products with those of the combustion products it is possible to save energy. This is an area that warrants further investigation.

The theory was that constant flue gas flow rate was not the most efficient way of operating a bakery oven. A better approach was to optimise the gas flows in and out of the oven (as illustrated in Figure 1). For example, product changeovers will reduce gas volumes released from products as will times of low product throughput. In both examples, the fixed speed flue gas fans will create low pressures inside the oven chambers, resulting in oven cooling through the cool air drawn into the oven. A variable speed drive fan linked to the combustion controls has potential to reduce oven cooling when low burner fire occurs.

To prove this theory, work was linked with measurements made by Spooner Industries on an instrumented single chamber test oven (see Figure 13). Gas consumption was measured for three different oven set-ups:

- High exhaust flow with no purge damper, which is common in small, craft bakeries, but not in modern commercial bakeries
- Exhaust reduced to simulate 'fixed speed' system to be more representative of a modern bakery oven
- Excess air minimised and exhaust set to balance oven. This achieved 42% reduction in energy consumption over the baseline measurements in the test oven.
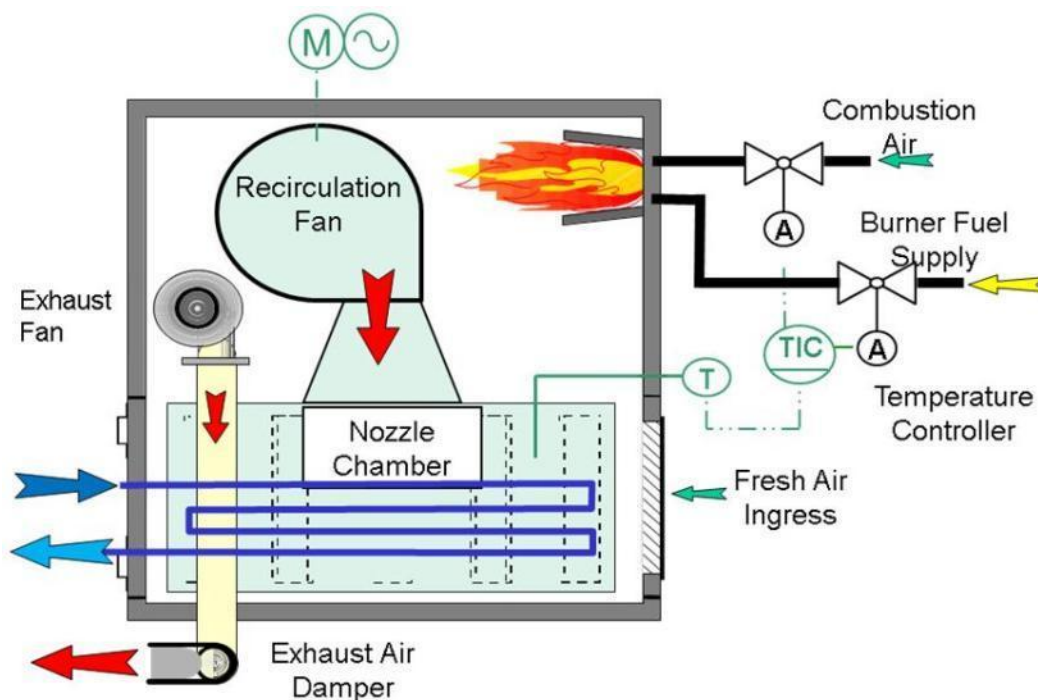

Figure 13: Single chamber test oven at Spooner Industries used to measure gas use for three different oven set-ups

Energy savings on the test oven were substantial, of the order of 42%, when compared with the baseline measurements. Calculations were made by Spooner Industries to scale-up this work to industrial ovens that operate with lower heat losses and for longer periods with the same heat load. Analysis showed that this technology could provide gas savings of 4.7% if applied to a commercial oven, saving £14,000 per year in gas.

There are approximately 89 UK industrial bakery sites, each with an annual energy bill of £865k, for which the ovens are responsible for £290-380k (Carbon Trust, 2010). Assuming energy prices have inflated by an average of 2% p.a. over the 4-year period since the report was written, each oven energy bill is £314-411k, giving a total for the bakery sector of £27,946-36,579k. A 4.7% saving in oven gas costs would save the UK bakery sector £1,313-1,719k (£1.3-1.7m) per annum.

Adopting this technology depends on the condition of the existing bakery ovens. Therefore, conclusions on savings and payback from the calculations were that:

- A modern commercial oven with a suitable burner and existing ratio controller will require minimal investment, which will pay back in one year.
- Many industrial bakery ovens are more than 5 years old and do not have suitable burners or controllers. Further interventions are likely to be required on a case by case basis, depending on existing equipment.
- Additional gas savings may be available by adding heat recovery technology. Estimated total cost savings of around 7.2% are possible.

CONCLUSIONS

Work reported here on gas flow optimisation showed that savings of 4.7% were possible by linking variable speed flue gas fans with combustion control. These savings do not seem that significant until the costs for operating an industrial bread oven are calculated. Each of these ovens will cost over £300,000 in gas to operate each year and so 4.7% represented £14,000 in annual savings. This is just for reducing flue gas fan speed at times of low product throughput so that oven cooling is minimised.

There remains the additional potential to link flue gas fan speed with product gas characteristics. This will require an understanding of the gas volumes released from products during baking, as demonstrated in this report. A fixed speed flue gas fan will draw the same quantity of gas through each flue despite different gas volumes being available from the products and combustion gases. Data on flow meter readings for non-condensable gases from bread baking showed that steam was the major gas responsible for flue gas volume. It would be sufficient to base a control system on this assumption because steam was around 95% of the volume. Measurement of weight loss and therefore steam generation is easy to implement.

Further energy reductions are possible by challenging the core temperatures used to confirm that bread and baked products are baked. This was investigated as part of Campden BRI member funded research project 129917, and reported in R&D Report 350 (Tucker, 2013). It evaluated reducing the core bread temperature from 94-96°C down to 90-92°C and did not find reasons why this could not be implemented. One of the challenges in making this bake time reduction was in controlling the water content of the bread.

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ACKNOWLEDGEMENT

APPENDIX 1: Calculation (estimation) of fermentable carbohydrate used during aerobic dough fermentation – stage 1

We make the assumption that all of the oxygen in the gas bubbles is available to the yeast for fermentation. This is a reasonable assumption; however, there will competition for oxygen between yeast and ascorbic acid. Ascorbic acid is added as an oxidising agent and will only work in its oxidising form after it has reacted with oxygen to convert it to dehydroascorbic acid. Since ascorbic acid is added in quantities of about 50-100 ppm it is not likely to require much oxygen for this conversion.

Data from Daniels and Fisher (1976) suggested that about 65 mmol of CO_2 was released from a 400 g loaf. Scaling weight was about 453 g. This will include both aerobic and anaerobic stages of fermentation.

Step 1: Calculate the volume of oxygen in freshly mixed dough

To calculate the mass of fermented carbohydrate used up in the <u>aerobic stage</u>, we assume that 15% by volume of the dough at the end of mixing is air, and that 20% of air is oxygen. Daniels and Fisher (1976) used a test bakery Tweedy, in which 13-16% air entrainment by volume is typical.   Air is about 20% oxygen, 80% nitrogen.   Percentage of oxygen (O_2) in dough by volume = 15 x 0.2 = 3%

Step 2: Calculate the volume of oxygen in the dough

A typical dough density at the end of mixing in under atmospheric pressure is 800 kg.m^{-3}.   Dough volume = (453 / 1000) / 800 = 0.000566 m^3 or 0.566 litres.   Oxygen volume = 0.000566 x 0.03 = 0.000017 m^3 or 0.017 litres.

Step 3: Calculate the number of moles of oxygen in dough

The number of moles occupied by this volume is calculated by assuming that oxygen is an ideal gas. For an ideal gas at STP (273K and 1 atmosphere pressure) 1 mole occupies 22.4 litres or 0.0224 m^3.   If we assume that the dough at the end of mixing is at 30°C (303K), we can correct the volume of an ideal gas for this temperature.   Volume at 30°C = (303 / 273) x 22.4 = 24.9 litres   Number of moles oxygen in 453 g dough = 0.017 / 24.9 = 0.00068 moles (6.8 x 10^{-4}).

Step 4: Calculate the number of moles glucose used by this oxygen

Aerobic fermentation of glucose follows Equation 1.

$$C_6H_{12}O_6 \quad + \quad 6O_2 \quad \rightarrow \quad 6CO_2 \quad + \quad 6H_2O$$

The stoichiometric ratio of fermentable carbohydrate (taken as glucose) to oxygen is 1 : 6.

Number of moles glucose = 0.00068 / 6 = 0.000113 moles (1.13×10^{-4}).

Step 5: Calculate the mass of glucose

The molar mass of glucose is 180, calculated from $C_6H_{12}O_6$, with atomic masses of carbon, hydrogen and oxygen as 12, 1 and 16 respectively.

Mass of glucose = 0.000113 x 180 = 0.02 g.

Step 6: Calculate the number of moles and volume of CO_2 from the aerobic fermentation

Volume of oxygen in 453g of dough is 0.017 litres.
The stoichiometric ratio of oxygen to carbon dioxide is 1 : 1.

Volume of CO_2 = 0.0000017 m^3 or 0.017 litres
Number of moles CO_2 = 0.00068 moles (6.8×10^{-4}).

Step 7: Calculate the percentage of starch used during anaerobic fermentation

A typical bread recipe will contain approximately 60% flour by weight (recipe will be flour 100, water 62, yeast 2.5, minor ingredients 2.0, salt 1.5).
Flour is approximately 70% starch by weight.

Mass of starch in 453 g dough = 453 x 0.6 x 0.7 = 190.3 g

Starch is composed of a series of glucose molecules and so it is reasonable to base the calculations on fermented starch by using glucose.

Percent of starch (glucose) used in aerobic fermentation stage = (0.02 / 190.3) x 100 = 0.01%

Mass of fermentable carbohydrate used during the aerobic stage of fermentation is 0.02 g (for a 453 g dough mass).

APPENDIX 2: Calculation (estimation) of fermentable carbohydrate used during anaerobic dough fermentation – stage 2

The assumption is that after the oxygen from air bubbles is used by the yeast in its aerobic phase the fermentation converts to anaerobic and follows Equation 2. There will be a small amount of oxygen that the yeast can utilise from dissolved oxygen in the dough water but it is generally considered that yeast obtains its oxygen from the carbohydrates such as glucose (Reed and Nagodawithana, 1991).

Data from Daniels and Fisher (1976) suggested that about 65 mmol of CO_2 was released from a 400 g loaf. Scaling weight was about 453 g. This will include both aerobic and anaerobic stages of fermentation.

Calculations on the aerobic stage of fermentation suggested that for a 453 g dough mass, 0.00068 moles (0.68 mmol) of CO_2 are generated, which occupies a volume of 0.017 litres. This suggests that the vast majority of CO_2 is generated during anaerobic fermentation.

Step 1: Calculate number of moles glucose required to generate 65 mmol of CO_2

Anaerobic fermentation of glucose follows Equation 2: $C_6H_{12}O_6 \quad \rightarrow \quad 2CO_2 \quad + \quad 2C_2H_5OH$ The stoichiometric ratio of fermentable carbohydrate (taken as glucose) to CO_2 is 1 : 2. Number of moles glucose = (65/1000) / 2 = 0.0325 moles.

Step 2: Calculate the mass of glucose

The molar mass of glucose is 180, calculated from $C_6H_{12}O_6$, with atomic masses of carbon, hydrogen and oxygen as 12, 1 and 16 respectively. Mass of glucose = 0.0325 x 180 = 5.85 g.

Step 3: Calculate the percentage of starch used during anaerobic fermentation

A typical bread recipe will contain approximately 60% flour by weight (recipe will be flour 100, water 62, yeast 2.5, minor ingredients 2.0, salt 1.5). Flour is approximately 70% starch by weight. Mass of starch in 453 g dough = 453 x 0.6 x 0.7 = 190.3 g Starch is composed of a series of glucose molecules and so it is reasonable to base the calculations on fermented starch by using glucose. Percent of starch (glucose) used in aerobic fermentation stage = (5.85 / 190.3) x 100 = 3.1%

Mass of fermentable carbohydrate used during the anaerobic stage of fermentation is 5.85 g (3.1% for 453 g dough mass).

APPENDIX 3: Recipes for baked products used to measure gas flow rates in a vacuum oven

Table A1: Bread - 400g open top white bread

Component	Weight (g)
Bread Flour	1500
Hard Fat	15
Water	918
Salt	22.5
Yeast	30
Improver	15

Table A2: Low ratio cake - 300g batter scale weight

Component	Weight (g)
Soft Margarine	500
Soft Flour	500
Caster Sugar	500
Egg	500
Baking Powder (SAPP 28 & Bicarb)	15

Table A3: High ratio cake with SAPP40 - 300g batter scale weight

Component	Weight (g)
Heat Treated Flour	400
Caster Sugar	460
Shortening	232
Emulsifier	8
SMP	28
Salt	4
Baking Powder (SAPP 40 & Bicarb)	15
Water	220
Whole Egg	320
Glycerine	32

Table A4: Low ratio chocolate cake with SAPP28, pH 8.5 - 300g batter scale weight

Component	Weight (g)
Soft Margarine	500
Soft Flour	500
Caster Sugar	500
Egg	500
Baking Powder (SAPP 28 & Bicarb)	15
Cocoa Powder	100

Table A5: Plain scones - 68g scones

Component	Weight (g)
Soft Flour	350
Baking Powder	17.5
Milk	196
Cake Margarine	87.5
Caster Sugar	77
Salt	1.5
Egg	21

Table A6: Plain muffin cake - 64g muffins

Component	Weight (g)
Soft Flour	250
Caster Sugar	125
Baking Powder	5
Bicarbonate of Soda	5
Milk	150
Vegetable Oil	60
Egg	50

APPENDIX 4: Measured gas flow rates in a vacuum oven
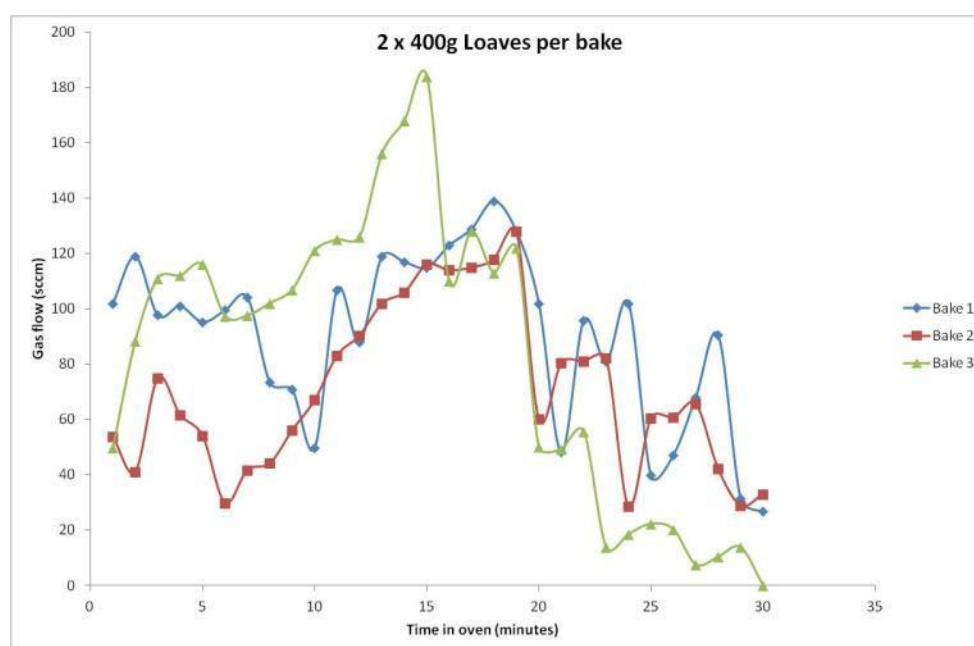
Figure A1: Gas flow measured with a flow meter during baking of 2 x 400g white open top bread, in a vacuum oven at 200°C, showing 3 replicate bakes
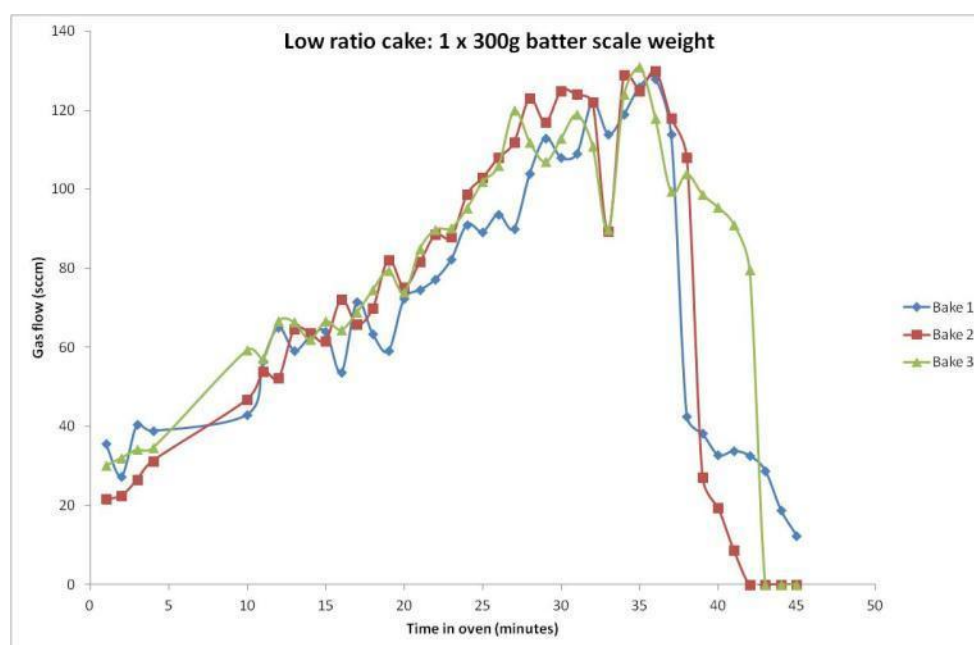
Figure A2: Gas flow measured with a flow meter during baking of 1 x 300g low ratio cake, in a vacuum oven at 200°C, showing 3 replicate bakes
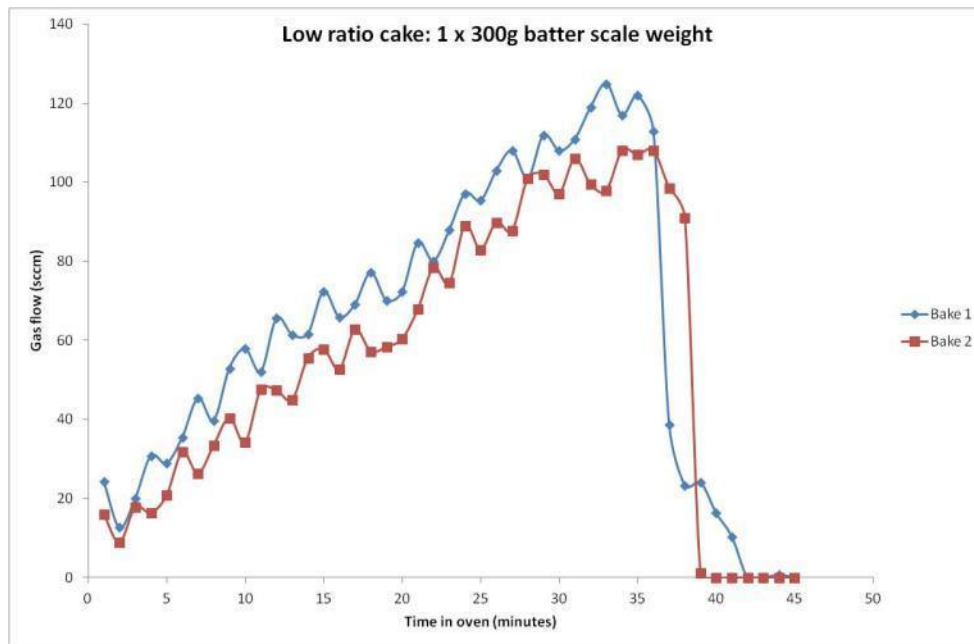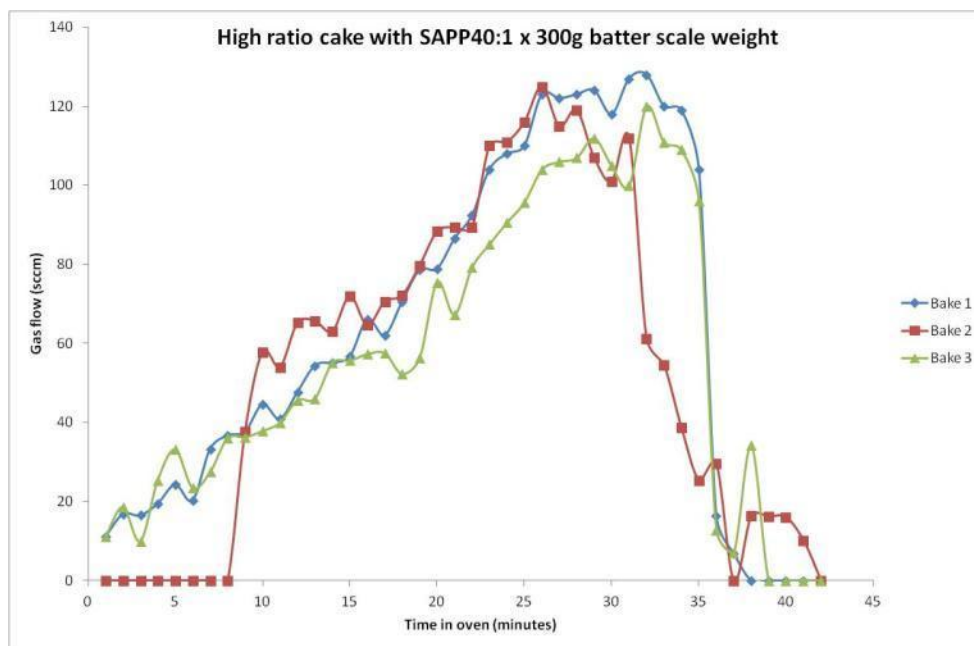
Figure A3: Gas flow measured with a flow meter during baking of 1 x 300g low ratio cake, in a vacuum oven at 200°C, showing 2 replicate bakes

Figure A4: Gas flow measured with a flow meter during baking of 1 x 300g high ratio cake (raising agent SAPP40), in a vacuum oven at 200°C, showing 3 replicate bakes
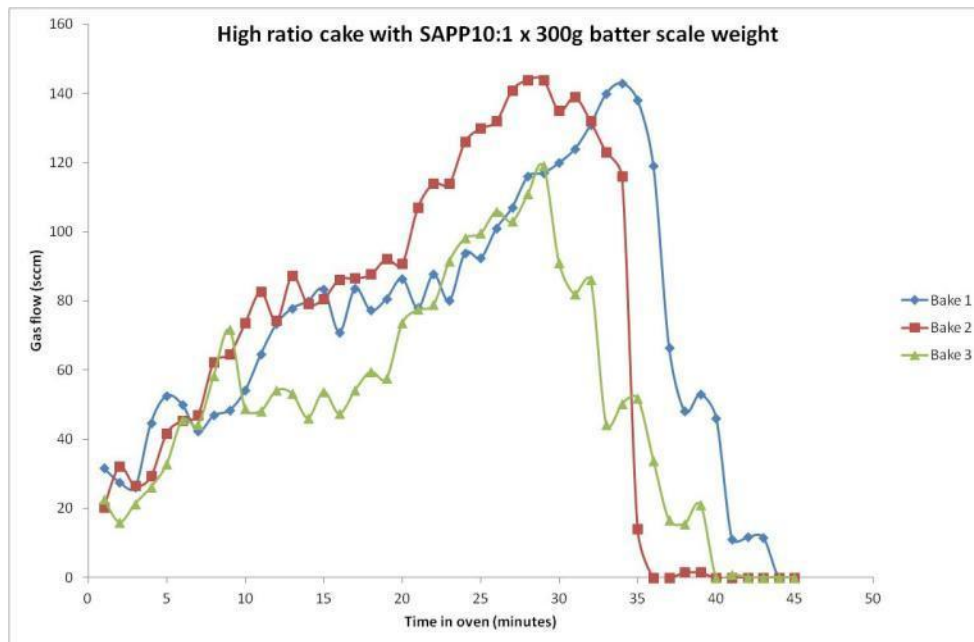
Figure A6: Gas flow measured with a flow meter during baking of 1 x 300g high ratio cake (raising agent SAPP10), in a vacuum oven at 200°C, showing 3 replicate bakes
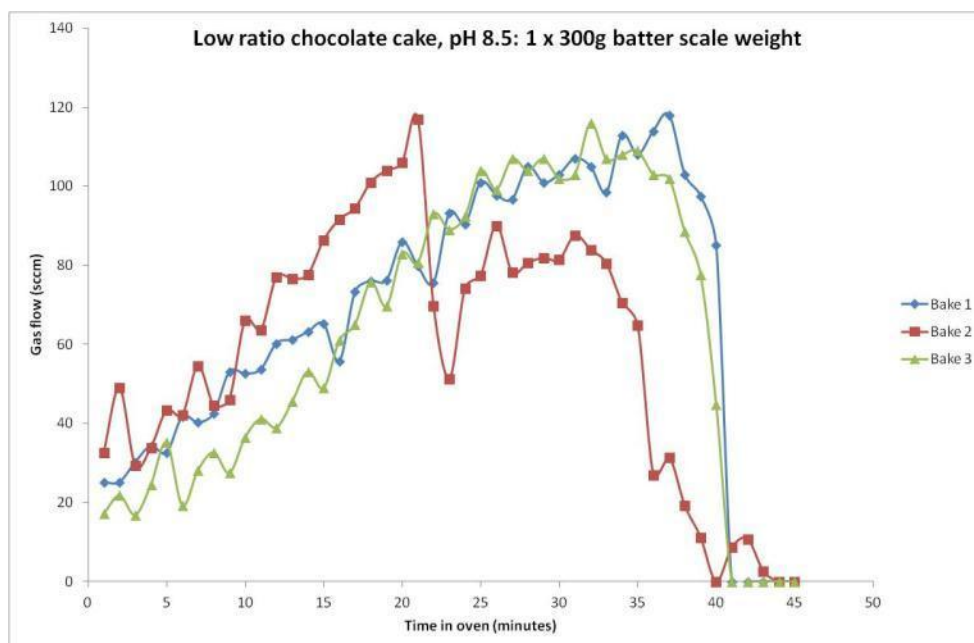

Figure A7: Gas flow measured with a flow meter during baking of 1 x 300g low ratio chocolate cake (pH 8.5), in a vacuum oven at 200°C, showing 3 replicate bakes
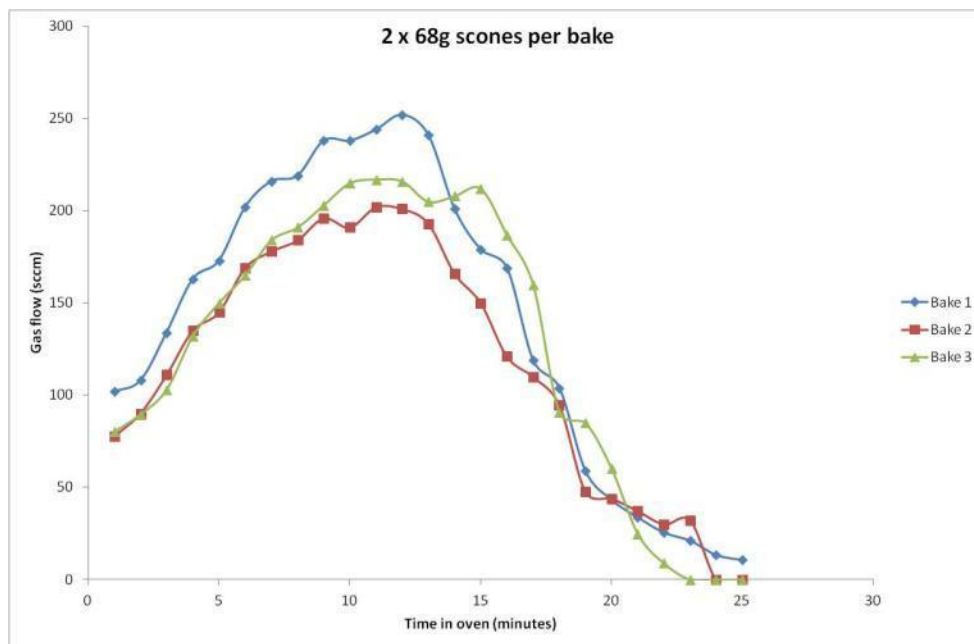
Figure A8: Gas flow measured with a flow meter during baking of 2 x 68g plain scones, in a vacuum oven at 200°C, showing 3 replicate bakes
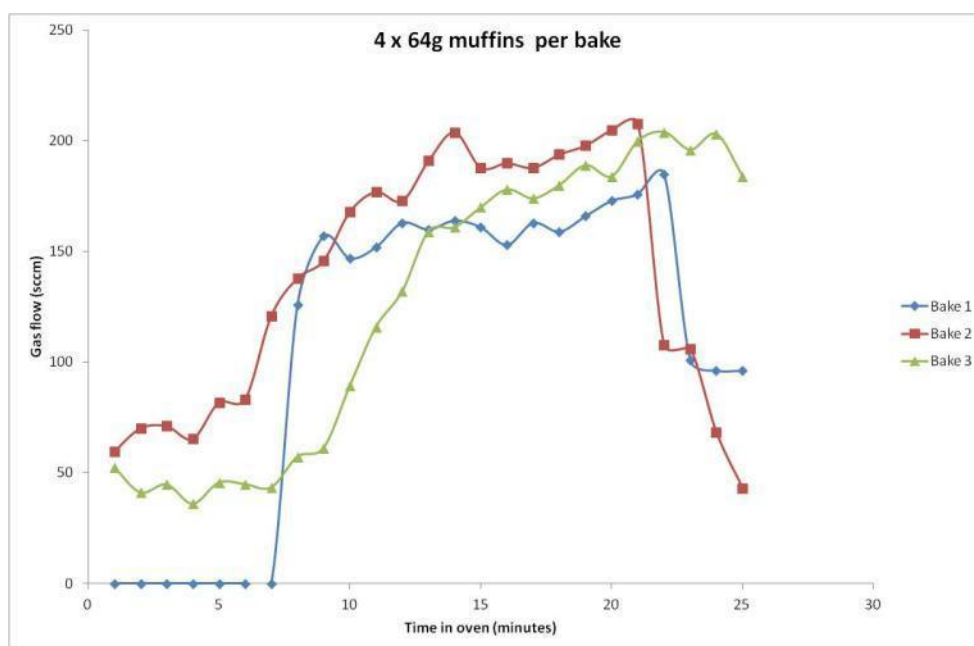

Figure A9: Gas flow measured with a flow meter during baking of 4 x 64g plain muffins, in a vacuum oven at 200°C, showing 3 replicate bakes