ABSTRACT

Achieving rapid baking in industrial tunnel ovens, while maintaining adequate product quality is a significant challenge. The application of excessive heat fluxes to a low-diffusivity heterogeneous food product can easily yield a product of poor quality (color, texture, flavour). It is desirable to optimize the application of heat on a transient basis during the baking process in order to minimize bake times and achieve an acceptable set of product responses (e.g. color, height, crust hardness, crumb moisture, weight loss). The magnitudes of the convective, radiative, condensing/evaporating and conductive heat fluxes dictate the quality of the baked product and the process efficiency.

By mapping the applied fluxes with time a “baking comfort zone” can be established. The map can be developed to indicate minima and maxima flux values and/or to identify an optimal heating profile. The baking comfort zone for a given product provides a useful visual indicator, which can be related to a similar indicator of product responses to improve understanding of the baking process. Furthermore, provided adequate instrumentation is available, the baking comfort zone can be utilized (i) by the operator of an oven at the process control interface to ensure that an appropriate heating profile is being achieved in practice; and (ii) to replicate products in different ovens.

This concept is based upon baking tests conducted on a high performance research oven manufactured by APV Baker (UK) and installed in their research centre in Peterborough England.
1 Introduction

Thermal comfort has been defined as being that ‘condition of mind which expresses satisfaction with the thermal environment’ [1]. This notion can be difficult to translate into physical parameters, as for instance, a person can feel thermally comfortable in two different environments. The body’s fragile energy balance is controlled by vertical air temperature difference, floor temperature, draughts, clothing, humidity, body activity level, and asymmetry of thermal radiation. A multitude of combinations exist between these parameters which provide thermally comfortable conditions in a building.

The application of heat in industrial baking is distinct from that of maintaining thermal comfort in buildings, but by analogy a well baked product can be achieved by a number of combinations of heat fluxes (convective, radiative, conductive, condensation) and baking times. By baking a product within its ‘comfort zone’ the baker can seek to reduce time and energy requirements, while achieving an acceptable product. It is proposed that this concept could be employed to optimize future designs of oven.

2 Micro and Macro heat transfer transport during the baking

Crumb formation is largely due to chemical and biochemical reactions while crust formation relies mostly on physical mechanisms governed by condensation and evaporation (mass transfer). The porous crumb structure is mainly formed by a matrix of protein starch and lipid that encloses the minute gas cells. The ‘quality’ of the structure depends on the fermentation phase (bread) and the mixing phase (biscuit, bread and cake).

Within the crumb, see Fig. 1, conduction occurs in the solid phase while condensation and evaporation occurs within the gas cells. Mass transfer takes place by capillary flow and liquid evaporation from the cells and product surface.

Both crust and crumb are closely related. A too early crust formation will restrain volume expansion and create extra stresses within the cell thereby corrupting the crumb structure. The crust formation is ‘controllable’ by the evaporation/condensation taking place at the surface, that is the moisture loss (weight loss) [1]. The heat transfer mechanism at the surface due to evaporation and condensation is driven by an evaporation front, which delimits the crust region from the crumb region. This front is formed by water vapour evaporated from the hot end of the cells and the free liquid phase of the product. The evaporation front phenomenon has been discussed by Stear [2] and used successfully in many mathematical models of food products, especially bread ([3], [4], [5]).

The isothermal evaporation front close to the boiling point of water (<100°C) will move towards the centre of the baked product as the product dries out. The rate of change of the evaporation front is determined by internal and external heat and mass transfer. The temperature and water concentration on either side of the front will push this evaporation front towards the centre if the product’s external temperature increases, or if the water concentration on the outside decreases. The flow of vapour by diffusion from the evaporation front will slow down as it passes through the crust.

To understand the surface phenomenon the macro heat and mass transfers have to be considered. In any domestic or

![Figure 1. Micro and macro heat transfer effects in baking](image-url)
industrial oven the three major modes of heat transfer (conduction, convection and radiation) are present, but heat transfer due to evaporation and condensation is also significant. For example, Christensen and Singh [6] presented an energy and mass balance for a bread tunnel oven, which shows that the energy loss from the oven by radiation and convection are similar, but that each is less than the energy loss due to evaporation of water from the bread itself.

Therefore the energy balance at the food surface as simplified by some authors [7][8] is a gross approximation as it only considers conduction, convection and radiation heat transfer. Evaporation is very important in biscuit baking as this process consists mainly of driving the moisture off the product. Ashworth and Armitage [9] studied extensively solids-drying, which consists mainly of driving the moisture off the product. Evaporation is very important in biscuit baking as this process consists mainly of driving the moisture off the product. Their analysis is based on the heat balance between the three heat transfer mechanisms (conduction, convection and radiation) and the heat leaving due to evaporation (mass transfer). Many mathematical models for simulating heat and water transport during baking have used this combined heat and mass transfer balance [4], [10], [11], [12] and [13]. Rask and Hallström [4] estimated the drying rate for bread under baking as a function of the differential between the water vapour pressure at the evaporation zone and the partial pressure of water vapour contained in the air (Fig. 1). This differential could also be explained in terms of equilibrium relative humidity, ERH. This has been used by some authors to assess the absorption and desorption of water from hygroscopic bodies such as food products. Herrington and Vernier [14], defined ERH as the ratio between the partial pressure of water vapour at the product surface to the saturation partial vapour pressure of water in the air at a total pressure of 1 atm.

\[
ERH = \frac{P_{\text{eq}}}{P_{\text{sat}}} \quad T, P = 1 \text{ atm} \quad (1)
\]

This parameter measures the water actually present in the air at equilibrium divided by the amount which would be present if the air was saturated. A general combined heat and mass transfer balance can be written to describe the heat and mass transport occurring during the baking of food products. The rate of temperature change within the product being baked is equal to the sum of the different heat transfer inputs (by conduction, convection and radiation) and the rate of moisture exchange with the surrounding air:

\[
\rho_b c_p A \frac{\partial T}{\partial t} = Q_{\text{ce}} + Q_{\text{cond}} + Q_{\text{conv}} + Q_{\text{rad}} \quad (2)
\]

This equation Eq. 2 can be used as the basis of a mathematical model of heat and mass transfer in baking.

### 2.1 Conduction

In a conventional industrial tunnel oven, thermal conduction (Eq. 3) occurs solely between the conveyor band and the product. For a tinned product it also occurs between the tin and the product (where the two are in intimate contact). Hence, Fourier’s Law applies:

\[
Q_{\text{cond}} = k A \frac{\partial T}{\partial x} \quad (3)
\]

The band where the product lays can be either made of solid steel or mesh. Conduction is very limited as the contact surface area between the tins and the band/mesh are very small and a substantial thermal contact resistance exists. Similarly a thermal contact resistance is present between the band and a biscuit but also between a bread loaf and the tin walls.

### 2.2 Mass transfer (Condensation / evaporation)

In most industrial ovens low pressure steam is usually injected during the first few minutes of baking. Condensation occurs when the vapour temperature is lower than the saturation temperature of the air, \(T_{\text{sat}}\) [14] and it will continue until the product surface temperature \(T_s\) exceeds this temperature (see Fig. 2) [15]. During this time, the latent heat of vaporization \(h_{fg}\) is released and heat is transferred to the surface, with condensation forming at the surface of the product.

Stear [15] reported that the weight of a dough piece increases until the surface temperature exceeds the dew point temperature when no further condensation can take place. Once the water condensing at the surface of the product forms a film, a thermal barrier will develop and the rate of heat transfer will decrease (heat being transferred only through the condensate film at the product surface). The amount of heat released during condensation is very large and proportional to the latent heat of vaporization of steam. The other modes of heat transfer also raise the surface temperature and evaporation commences once the dew point temperature is exceeded (see Fig. 2). Both condensation and evaporation are driven by mass transport.

\[
Q_{\text{ce}} = \rho V h_{fg} C \frac{\partial C}{\partial t} \quad (4)
\]

<table>
<thead>
<tr>
<th>Condensation</th>
<th>Evaporation</th>
</tr>
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<tbody>
<tr>
<td>(T_{\text{sat}} &gt; T_s)</td>
<td>(T_{\text{sat}} &lt; T_s)</td>
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Figure 2. Condensation and evaporation

The mass transport phenomenon is the transient mass species differential between the water content of the air and the water
content at the surface of the product. Hence, this mass transport is related to equilibrium relative humidity (ERH). Indeed, the greater the amount of steam in the oven air atmosphere, the greater the partial vapour pressure of water in the air (\(P_{\text{sat}}\)) and the greater the mass transport driver from the humid air to the product surface.

The benefit of steam condensing at the surface has long been recognized in helping the glaze to form at the surface of a bread product [15]-[16]. Dersh [17] commented on the knowledge of the use of steam during the baking of bread, but most of the ground work and findings originate from Brownell [18]. In a humid atmosphere, the thermal characteristics of the steam will initially enhance the heat transfer to the product thereby helping to reduce the overall baking time, but on the other hand inhibiting the mass transport by evaporation may increase the bake time as the product retains a higher moisture content.

### 2.3 Convection

Convective heat transfer occurs in an oven between the air movement generated by water vapour, combustion gas or air forced at the surface of the product.

\[
Q_{\text{conv}} = hA(T_w - T_s)
\]  

(5)

The higher the heat transfer coefficient and the greater the temperature difference between the crust temperature and the oven air, the greater the convective flux. A boundary layer is created when a fluid flows over a solid. Milson and Kirk [19] concluded that the heat transfer coefficient is inversely proportional to the boundary layer thickness. The thickness of this boundary layer tends to be minimal at the leading edge of a plate and often causes edge burning in biscuit baking. Many authors have discussed the benefit and detriment of convection during baking. In their optimization of the baking processes, both Christensen et al [20] and Mälkki et al [21] concluded that more uniform colored bread can be obtained using forced convection instead of free convection, and bake time can also be reduced as the weight loss (water loss) was greater. Amongst heat transfer enhancement techniques, the recirculation of air in ovens has been used for many years. This allows a more uniform air temperature distribution and improves product quality uniformity (shape, color). More radical enhancement techniques have also been used with great success in more recent years. Several authors [22], [22], [23] have described the effects of jet-impingement technology in baking. Impinging jets reduce the thickness of the boundary layer (see Fig. 3) thanks to the high velocity air flow being orthogonal to the product surface and the associated increased rate of evaporation.

Wählby et al [24] investigated impingement baking and concluded that the baking time was similar to a traditional oven but at a much lower air temperature. For relatively large meat products overall browning was more uniform. However, they concluded that impingement did not influence significantly the browning of bun although it was achieved in a shorter time.

### 2.4 Radiation

The rate of thermal radiation transferred between a hot surface at \((T_{rh})\) to a colder surface at \((T_{sk})\) is expressed by Eq. 6. The view factor \(F_{r \rightarrow s}\) represents the fraction of the energy leaving the radiating surface \(r\) to the product skin surface \(s\). The emissivity of the product is also of importance and will change slightly during the baking process as the product darkens.\[Q_{\text{rad}} = \varepsilon F_{r \rightarrow s} \sigma A(T_{rh}^4 - T_{sk}^4)\]  

(6)

The most efficient wavelength for baking bread according to Pyler [25] is between 3 to 6\(\mu\)m (long-wave or FIR). Skjöldebrand and Anderson [26] as well as Horace and Smith [28] have discussed the absorption of radiant heat from different wavelengths.

Baked products are relatively moist and as discussed previously a film of water usually occurs during the first minutes of the bake if steam is applied at the surface of the product. Later on during the bake, evaporation from the product will also leave a thinner water layer on the surface. From the absorption curve for a water layer of 3mm (Fig. 4), it can be seen that the water will absorb most of the radiant energy in the medium wave infra-red (1.4 - 2.6\(\mu\)m) while below 1.4\(\mu\)m, it is relatively transparent. If a short-wave radiator (NIR) with a peak radiation of 0.9\(\mu\)m was used then some of its radiation would be absorbed by the water (see Fig. 4, intersection between energy distribution curve from radiator and water absorption curve for a 3mm water layer) while the remainder penetrates into the baking product. However Skjöldebrand and Anderson [26] estimated that 50% of the incident infrared heat would be reflected in the short wave, while only 10% will be...
reflected in the long wave.

Sakai and Hanzawa [27] studied the applications of far and near infrared in foods as well as baking and found out that NIR had a greater penetrating power than FIR during bread baking. NIR heating tended to leave the crust wet, while FIR developed more color to the surface by increasing further the surface temperature. Their findings also match with the original work of Ginzburg [29] who established the short wave penetration depths\(^1\) of several food products (including bread for which penetration depth was measured as 11-12 mm at 1\(\mu\)m). Depending on the thickness of the product, Skjöldebrand and Anderson [26], have also proved that bake time for baking bread and biscuit could be reduced between 25% to 50% by using NIR.

3 Theoretical concept of BCZ\(^2\)

Research is being conducted to examine increased rates of heat transfer in baking in order to reduce bake time while keeping the product responses (color, volume, weight loss...) within acceptable tolerance bands. A research rig batch oven, the Thermal Performance Research Oven (TPRO) has been designed [30] to explore existing heat transfer conditions as they exist in current baking ovens, and to permit baking beyond conventional limits. Sensitivity and repeatability studies [31] (based on real time measurements of 52 temperatures, 8 air pressures and one air humidity node) demonstrated that the results from the various measurements could be obtained with a COV\(^3\) of less than 1.5% for a steady state regime. An optimization approach for a Madeira cake product was developed from a design of experiments (DOE). Process variables measured were, oven temperature, air velocity impinging on the product, radiation temperatures, humidity and band speed. Product responses measured were bake time, product surface colors, crust hardness, density, volume, moisture, weight loss, crumb moisture, internal temperature and overall dimensions. A 16.6% bake time reduction has been achieved [31] by keeping the relevant product responses within benchmark tolerance which represent a significant saving.

From this experimental study, a concept referred to here as a Baking Comfort Zone, has been developed to illustrate the effects of applying different heat fluxes to a baked product. The conduction, radiation and convection fluxes were computed from temperatures and air flows, measured in real time, and the condensation flux was estimated.

Figure 5. illustrates the normalized heat flux distribution occurring during the baking of a Madeira cake.

\[\text{Figure 5. Normalized heat flux distribution during Baking of a Madeira Cake}\]

\[\text{Normalized Heat Flux Distribution during Baking of a Madeira Cake}\]

The condensation heat flux is predominant during the first 18% of the bake time and then decreases to zero flux as soon as the product surface temperature exceeds the dew point temperature. The conduction heat flux has the lowest magnitude; it decreases and stabilises because the temperature difference across the tin material reaches steady state very quickly. The convection and radiation heat fluxes are functions of the product surface temperature, and the temperature of the

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1. The measurement of penetration depth takes place when 37% of the radiation energy is unabsorbed
2. Baking Comfort Zone
3. Coefficient of Variance: standard deviation expressed as a percentage of the mean
oven air/radiant surfaces. The radiation heat flux is a combination of direct and indirect radiation. As the product surface increases the relative heat flux values decrease.

Optimizing a baking process is difficult as many variables can interact and estimating the effect of one transient variable (temperature, humidity) on a particular product response (color) can be challenging. The mapping of heat fluxes for a baking process can aid understanding of how the chemical transformation of the product (starch gelatinization, Maillard reaction) relates to various combinations of heat flux, by type and magnitude. It can also help to optimize the application of each heat flux during a bake to provide a higher quality product in a shorter bake time.

To visualize these fluxes on one “map” several forms of representation are feasible. Distinct representations may be developed to meet the respective needs of bakers when controlling ovens during baking operations, test engineers when commissioning an installed oven, and oven designers when developing future ovens. However, for simplicity one form of map is described here.

The fluxes defined, can be plotted on radial axes with the height axis representing the elapsed bake time Fig. 6 (A). The points plotted on each radius, at the base of this cylinder, represent the magnitude of the fluxes at the start on the baking Fig. 6 (A). The simple polygon represented by Fig. 6 (A) provides a visual shape for describing the relative net flux values at some elapsed time, t, in the baking process.

Fig. 6 (B) represents the oven conditions at the early stage of baking. This imaginary quadrilateral shape is called a ‘heat flux map’. At the early stage of the bake, the dough is much colder than the ambient air and the radiating surfaces of the oven surfaces. Hence, all fluxes are relatively large (close to the outer radius of the base disc), especially the condensation flux. The heat flux map is then transformed from this early stage of the bake until the end of the baking period (Fig. 7), when the product surface temperature is relatively close to the air and radiating surface temperatures.

As the bake progresses the tin, base and core temperatures increase and superficial rates of convection, radiation and conduction become significantly less than they were in the first few minutes of the bake, unless some imposed change is made to the oven settings see Fig. 6 (B). For example, steam is commonly used only during the first quarter of a bake to maximize the rate of heat transfer to the product during this stage. Later, towards the end of the bake product evaporation declines significantly as the product dries off. The map illustrated here only shows the condensation flux, that is the imposed fluxes for transferring heat to the product and so the eventual shape of the heat flux map may become triangular, see
Fig. 7. Starting from the initial map, it is possible to apply several combinations of heat flux, or paths Fig. 7, to reach the end of the bake. Fig. 8 (A, B) shows two possible paths to reach a final heat flux map. As the flux distribution with time is very different from case (A) to (B), the bake time would also differ. Although the scenario in Fig. 8 (A) gives a longer bake time than for that in Fig. 8 (B) the product might, for example, have a too pale color or a poor texture than that for Fig. 8 (B), which may be too dark as all the initial heat fluxes were too high. There are several prospective heat flux paths for obtaining a product of satisfactory (edible) quality. Beyond some limiting paths only unsatisfactory products will emerge. At each stage of the bake, there is effectively a minimum and maximum heat flux map Fig. 9.

The maximum heat flux map is determined by the maximum amount of heat that a product can absorb beyond which the final product is of poor quality (too dark, too dry) and the minimum with a product that is too pale, too moist or for which the bake time is too long. Assuming a maximum bake time of 40 minutes, development of the intermediate heat flux maps follow the same logic applied as for the starting and the final shape of the heat flux map. Fig. 10 (A) shows intermediate heat flux maps for several stages in the bake. Each of these, Fig. 10 (A) can be changed by altering the oven settings during the bake (as applies generally for multi-zone tunnel ovens).

Each of the heat flux maps represents an imaginary surface which characterizes the minimum and maximum heat flux for the considered product. If the applied heat flux is close to the origin, the product will tend to be under-developed, under-baked at its centre, and too pale. However, when close to the maximum values the color will be darker, the crumb set, and the moisture content will be less. Therefore a tubular volume exists which describes a product of optimal quality (within an accepted tolerance band). Assuming that between an elapsed time of 30 and 40 minutes the product quality remains within the tolerance band, a BCZ can be defined by the volume between the two baking zones for the respective bake times of 30 and 40 minutes, see Fig. 10 (B).

This volume (mountain shape) Fig. 10 (B) represents the BCZ for a particular product. The research challenge is to optimize this volume for the product under study and identify acceptable tolerance bands. The closer the heat flux map is to the top of the BCZ the longer the bake time. The ideal product is usually that which has similar characteristics to a benchmark product lying...
within the BCZ but with the least bake time. The product baked in these optimized conditions can be defined by the oven settings within the imaginary optimized BCZ represented by the volume represented by Fig. 10 (B).

If the heat fluxes to the product could be measured directly in real time, it would be possible to develop a real-time graphic imaging interface that would show how the heat flux maps are changing during the bake. Further, control algorithms might help to control the transient application of heat to achieve the optimum BCZ. The heat flux map paths displayed by Fig. 8 could be altered at any time within the performance limits of the oven. For instance, more radiation might be required half way through the bake, hence the shape of the overall heat flux map would change. The best BCZ profiles for any baking product could be established either by experimentation (Design of Experiments techniques [31], [32]) or by a more sophisticated feedback control system for example using the Qualivision system (online color and shape monitoring [33]) and an appropriate control algorithm (such as fuzzy logic). This way, BCZ profiles for any baked product could be established and entered into a database that would be used as a control reference, so that the current profile would match the optimized reference.

To estimate the optimal BCZ, and the best heat flux path, it is important to relate the process variable changes (heat fluxes) to product response changes such as color, crumb moisture, height, etc. The heat flux map Fig. 10 (C) is considered to be optimized if the product responses are within the tolerance band. For any heat flux map (variables) a corresponding product zone (responses) exists, see Fig. 11. A heat flux map is accepted as part of the BCZ, if the response zone is within the tolerance band. At any instant during the bake there is an optimum range of conditions defined by the fluxes that will promote the final optimized product.

To apply this concept of BCZ in real baking ovens, for implementing feedback control loops to the heating systems, measurement of heat fluxes at the product surface is desirable. The response of the instrumentation will be critical and the time lag between measurement and control should be minimized. The thermal response time of the oven should be kept as small as possible. Control algorithms based on fuzzy logic or neural networks may well be appropriate as thermal processes in baking are non linear and difficult to predict because they are dictated by bio-chemical reactions.

To optimize the baking process, one can imagine a control system linked to the process variables that would adjust the heat flux maps in order to attain the response zone within the tolerance band in the fastest time. This way, an ideal profile (variables/responses) versus time could be built for any product, thereby defining the set of optimal heat transfer conditions during the bake. The BCZ concept applies irrespective of oven type for a given product. It also encourages experimentation to see if a greater input by one flux is a good method, or whether a combination of two or more fluxes is desirable.

Measurement of heat flux at the product surface in real time is
a subject of ongoing research. As yet, it cannot be achieved easily and maintaining accuracy is difficult so it is more appropriate to measure the final product responses. Product surface temperature remains a measurement challenge and cannot be measured repeatedly. As yet, the BCZ concept is difficult to apply in practice, because of various measurement issues.

4 Conclusion

This paper describes the baking ‘comfort zone’ concept, identifies heat flux maps and discusses their use for optimizing the bake time of a cake product that has been the subject of a practical investigation with a high performance research oven. By mapping the applied heat fluxes with time a “baking comfort zone” can be established. The map can be developed to indicate minima and maxima flux values and/or to identify an optimal heating profile. The baking comfort zone for a given product provides a useful visual indicator, which can be related to a similar indicator of product responses to improve understanding of the baking process. On-line heat flux measurement for the product surface and an interface screen visualization software system is presently under investigation.

ACKNOWLEDGEMENTS

The authors would like to thank APV Baker for their continuing support of the research described in this paper. The experimental aspects of this project were conducted with a high performance Thermal Performance Research Oven manufactured by APV Baker (UK).

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