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HEAT FLUX MAPS FOR OVENS : BAKING COMFORT ZONES

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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 (colour, texture, flavour). It is desirable to optimise the application of heat on a transient basis during the baking process in order to minimise bake times and achieve an acceptable set of product responses (e.g. colour, 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 utilised (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.

Nomenclature

A	Cross sectional area	m^2
Cp_b	Bulk specific heat capacity of product	$J/kg \cdot K$
ε	Emissivity	
h	Convective heat transfer coefficient	$W/m^2 \cdot K$
h_{fg}	Latent heat of evaporation	J/kg
k	Conductivity	$W/m \cdot K$
P_{equ}	Water vapour pressure at product surface	Pa
P_{sat}	Saturation partial vapour pressure of water	Pa
Q_{ce}	Evaporation / condensation heat transfer rate	W
Q_{cond}	Conductive heat transfer rate	W
Q_{conv}	Convective heat transfer rate	W
Q_{rad}	Radiative heat transfer rate	W
ρ_b	Bulk density of product	kg/m^3
ρ_l	Density of liquid	kg/m^3
σ	Stephan-Boltzman constant	$W/m^2 \cdot K^4$
T_∞	Ambient temperature	$°C$
T_{rk}	Radiant heater surface temperature	K
T_s	Surface temperature	$°C$
T_{sat}	Saturation temperature of the air	$°C$
T_{sk}	Product surface temperature	K
V	Volume	m^3

1 Introduction

Thermal comfort has been defined in the ISO 7730 [1] standard, as being that 'condition of mind which expresses satisfaction with the thermal environment' [2]. This notion can be difficult to translate into physical parameters, as for instance, a person can feel thermally comfortable in two different environments. The two conditions defining thermal comfort are the control of both core and skin temperature to respectively 37°C and 34°C and the maintenance of the body's energy balance between heat gain (heat produced by the metabolism) and heat loss (by convection, conduction, radiation and evaporation/condensation). This 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. Although the term baking comfort does not yet exist in the jargon of bakers, it is proposed that this concept could also be employed to optimise future designs of oven. For years, the baking process has remained a 'black art' and knowledge has been passed down through generations of bakers.

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) [3]. 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 will create extra stresses within the cell thereby causing a corrupted crumb structure. The crust formation is 'controllable' by the evaporation/condensation taking place at the surface, that is the moisture loss (weight loss), see [4]. 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 phenomenon of evaporation front has been discussed by several authors ([5], [6]) and has been used sucessfully in many mathematical models of food products, especially bread ([7], [8], [9], [10], [11]).

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 evaporation front delimits the crumb from the crust. 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 transfer have to be considered. In any domestic or industrial oven the three major modes of heat transfer (conduction, convection and radiation) are present. However, heat transfer due to evaporation and condensation is also significant. For example, Christensen and Singh [12] 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. Their results show that the energy loss by the radiation and convection from the oven walls are almost as important as the energy loss by the evaporated water from the bread itself.

Therefore the energy balance at the food surface as simplified by some authors [13] and [14] is only 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 [15] studied extensively solids-drying and particularly the external heat and mass transfer controlling the drying rate for biscuit. 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 applied to simulate heat and water transport during baking have used this combined heat and mass transfer balance, [16], [17], [10] [18], [19] and [20]. Rask and Hallström [10] have estimated the drying rate of bread under baking as the 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 explain the absorbtion and desorption of water from hygroscopic bodies such as food products. Both Hardman [21], Herrington and Vernier [22], have used the same definition of 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 (P_{sat}) at a total pressure of 1 atm.

$$ERH = \left(\frac{P_{equ}}{P_{sat}}\right)_{T,\,P\,=\,1atm} \tag{1}$$

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:

$$\rho_b Cp_b A dx \frac{\partial T}{\partial t} = Q_{ce} + Q_{cond} + Q_{conv} + Q_{rad} \tag{2}$$

This equation (Eq. 2) can be used to generate 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 will also occur between the tin and the product (where the two are in intimate contact). Hence, from Fourier's Law:

$$Q_{cond} = kA\frac{\partial T}{\partial x} \tag{3}$$

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 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 [23]. Stear [24] who carried out substantial work in understanding the condensation/evaporation taking place during baking noticed that condensation will continue until the product surface temperature (T_s) has exceeded the dew point temperature (or the saturation temperature of the air, (T_{sat})) (see Fig. 2). During this time, the latent heat of vaporisation h_{fg} is released and heat is transferred to the surface, as a result condensate will form at the surface of the product.

During this stage, Stear [24] 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. The water condensing at the surface of the product forms a thermal barrier and will tend to slow down the heat transfer. The heat can then only be transferred through the film of water condensed at the product surface. The amount of heat released during condensation is very large and proportional to the latent

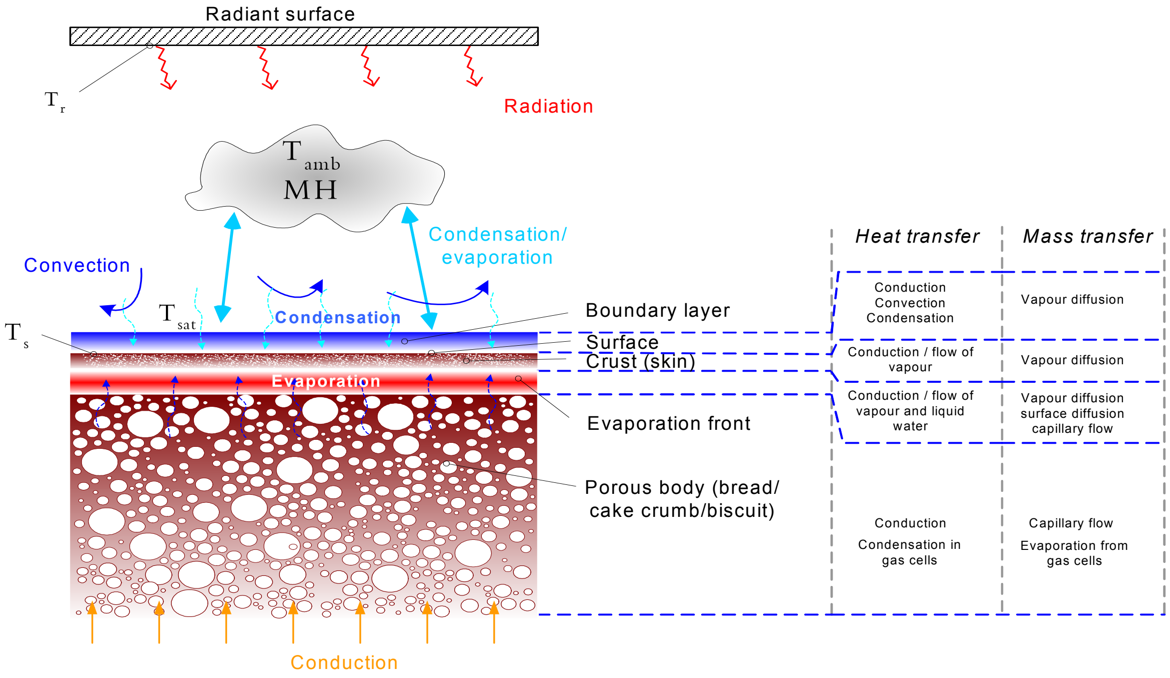

Figure 1. Micro and macro heat transfer effects in baking

heat of vaporisation of steam. The other modes of heat transfer will help the surface temperature to rise higher than the dew point temperature (saturation temperature), thereby initiating evaporation (see Fig. 2). Both evaporation and condensation are driven by mass transport.

$$Q_{(e,c)} = \rho_l V h_{fg}\frac{\partial C}{\partial t} \qquad (4)$$

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_{sat}) and the greater the mass transport driver from the humid air to the product surface.

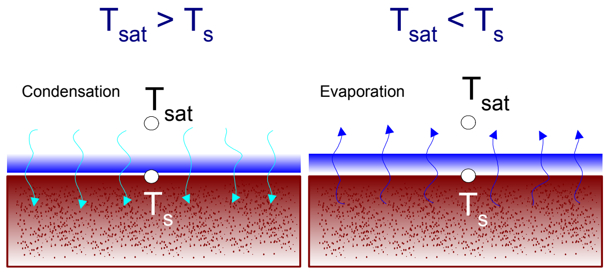

Figure 2. Condensation and evaporation

The benefit of steam condensing at the surface has long been recognised as an advantage and quality in helping the glaze forming at the bread surface for instance, [24]-[25]. Dersh [26] commented on the knowledge of the use of steam during the baking of bread, but most of the ground work and findings originated from Brownell [27]. 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 down the surface of the product.

$$Q_{conv} = hA(T_\infty - T_s) \qquad (5)$$

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 [28] 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 optimisation of the baking process, both Christensen et al [29], Mälkki et al [30] have concluded that more uniform coloured bread could be obtained using forced convection than free convection, and bake time was also 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, colour). More radical enhancement techniques have also been used with great success in more recent years. Several authors [31], [32], [33] have described the effects and the usage of impingement technology in baking. Impingement jets reduce the thickness of the stagnant air boundary layer (see Fig. 3) thanks to the high velocity air flow being orthogonal to the product surface and promote increased rate of evaporation.

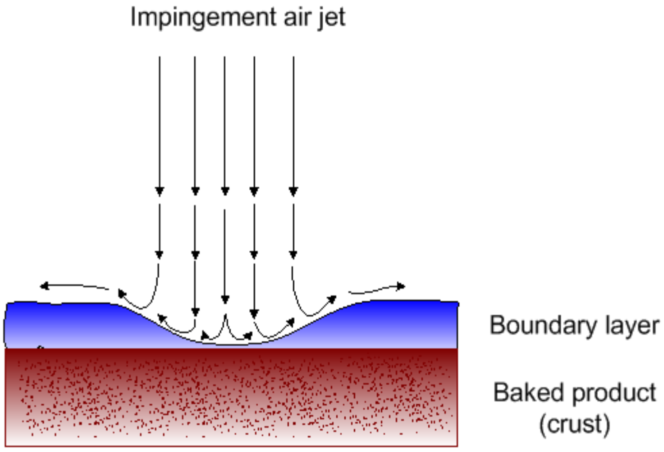

Figure 3. Effect on stagnant boundary layer of air jet impingement

Wählby et al [34] have investigated impingement baking and concluded that the bakingtime was similar to a traditional oven but at a much lower air temperature. For relatively large meat products overall browning was 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_{rk}) to a colder surface at (T_{sk}) is expressed by Eq. 6. The view factor $F_{r \to s}$ 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.

$$Q_{rad} = \varepsilon\sigma F_{r \to s} A(T_{rk}^{4} - T_{sk}^{4}) \qquad (6)$$

The most efficient wavelength for baking bread according to Pyler [35] is between 3 to 6µm (long-wave or FIR). Skjöldebrand and Anderson [36] as well as Horace and Smith [38] have discussed the absorption of radiant heat from different wavelengths.

Baked products are relatively moist and as discussed previously a film of water usually occur during the first minutes of the bake if steam is condensing 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. 3), it can be seen that the water will absorb most of the radiant energy in the medium wave infra-red (1.4 - 2.6µm) while below 1.4µm, water will only absorb a very small amount. If a short-wave radiator (NIR) with a peak radiation of 0.9µm 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) and some will penetrate into the baking product. However Skjöldebrand and Anderson [36] estimated that 50% of the infrared heat would be reflected in the short wave, while only 10% will be reflected in the long wave.

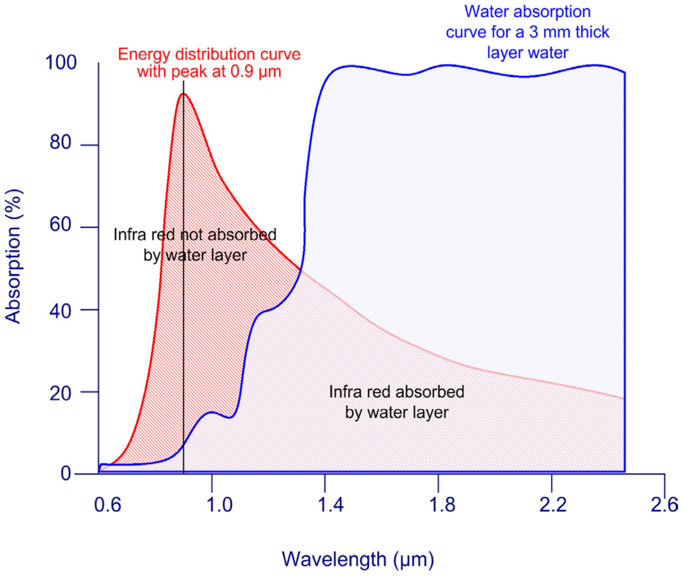

Figure 4. Absorption of infra-red radiation by a 3 mm thick layer of water with the superimposed energy distribution curve of a NIR radiant heater peaking at 0.9 µm

Sakai and Hanzawa [37] have 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, as NIR heating only left the crust wet, although FIR developed more colour to the surface by increasing further the surface temperature. Their findings also match with the original work of Ginzburg [39] who established the penetration depth[1] of several food products including bread for which penetration depth was measured to 11-12 mm at 1µm. Depending on the thickness of the product, Skjöldebrand and Anderson [36], 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]

Baking trials were conducted with a Madeira cake product and the heat fluxes were derived from temperatures and air flows, measured in real time. The evaporation flux was not estimated as the mass of water evaporated from the product could not be measured within the oven. Figure 5. represents the normalised heat flux distribution during the baking process of a madeira cake. The condensation heat flux is predominant during the first 18% of the bake time and then decreases to zero heat flux as soon as the product surface temperature has risen above the dew point temperature.

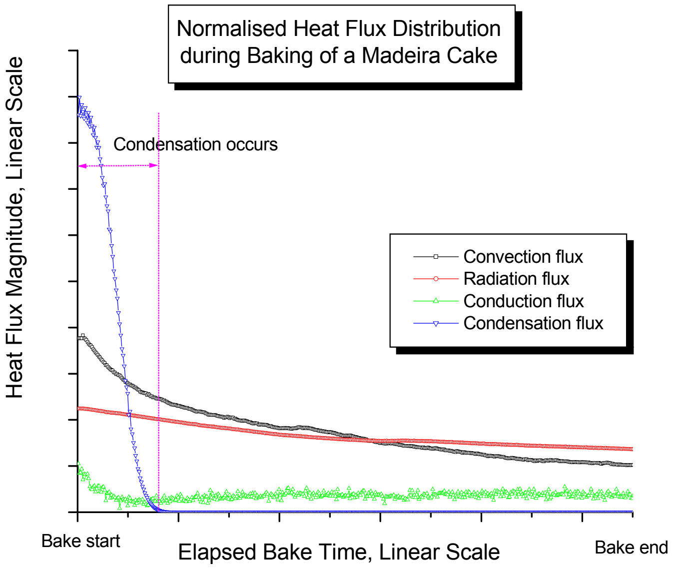

Figure 5. Normalised heat flux distribution

The conduction heat flux is the smallest of the heat fluxes. It decreases and stabilises because the .temperature difference accross the tin material reaches steady state very quickly. The convection and radiation heat fluxes are function of the product surface temperature, the oven air temperature and radiant temperature surfaces. As the product surface increases the relative heat fluxes decreases. The radiation heat flux is a combination of direct and indirect radiation.

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1. The measurement of penetration depth takes place when 37% of the radiation energy is unabsorbed
2. Baking Comfort Zone

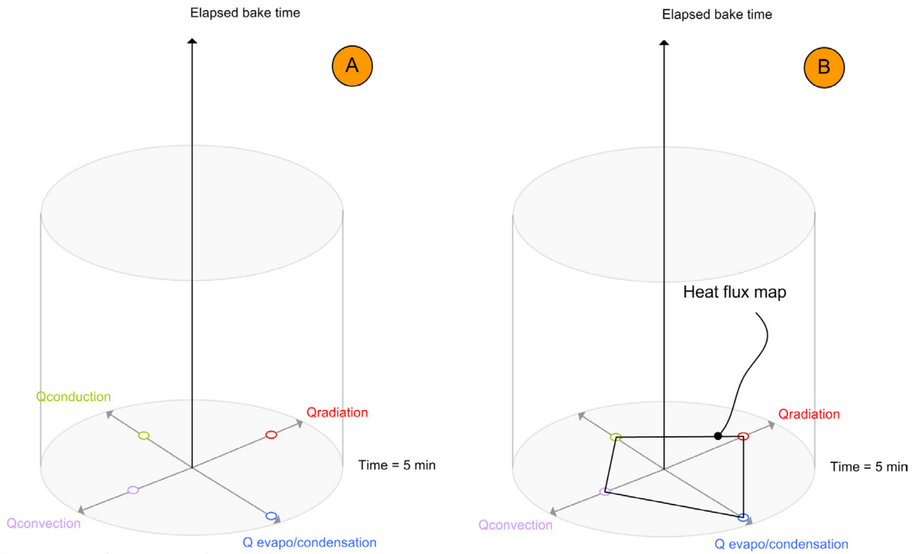

Figure 6. Concept of heat flux map

Optimising a baking process is difficult as many variable can interact and estimating the effect of one transient variable (temperature, humidity) on a particular product response (colour) can be challenging. The mapping of heat fluxes for a baking process can aid understanding of (i) how the chemical transformation of the product (starch gelatinization, maillard reaction) relates to various combinations of heat flux, by type and magnitude; and (ii) how to best apply each heat flux during a bake to provide a higher quality product in a shorter bake time.

To visualise these fluxes on one "map" several forms of representation are feasible. There may not be a single representation, which meets the needs of bakers when controlling the oven during baking operations, test engineers when commissioning (or diagnosing problems with) 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 radii of a cylinder 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 (C), when the product surface temperature is relatively close to the air and radiating surface temperatures.

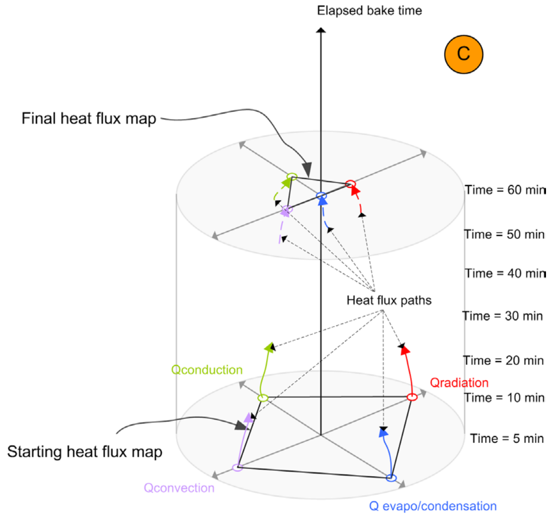

Figure 7. Initial and final shape of the heat flux map

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 maximise the rate of condensation 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 (C).

From the initial heat flux map, it is possible to apply several combinations of heat flux, or paths Fig. 7 (C), to reach the end

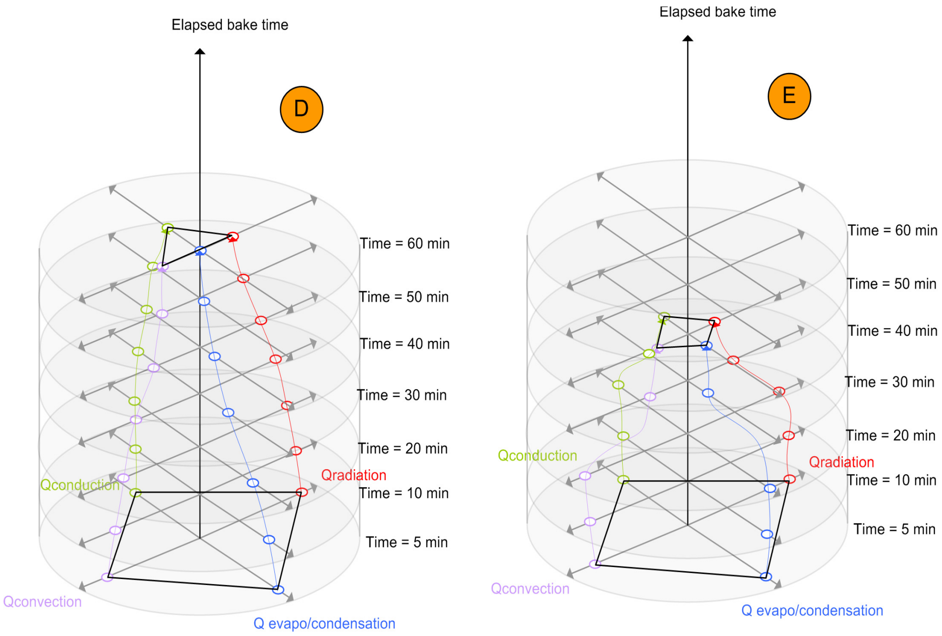

Figure 8. Plausible heat flux paths

of the bake. Fig. 8 (D, E) shows two possible heat flux paths to reach a final heat flux map. As the flux distribution with time is very different from case (D) to (E), the bake time would also differ. Although the scenario in Fig. 8 (D) gives a longer bake time than for scenario Fig. 8 (E) the product might, for example, have a too pale colour or a poor texture than that for Fig. 8 (E), which may be too dark as all the initial heat fluxes were too high. There are several 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 (F).

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 a minimum below which the product is too pale, too moist or 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 appliedas for the starting and the final shape of the heat flux map. Fig. 10 (G) shows the intermediate heat flux map for several stages in the bake. Each single heat flux map, Fig. 10 (G) 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 characterises 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 colour will be darker, the crumb set, and the moisture content will be less. Therefore there must exists a volume within this cylinder where a product of optimal quality will be baked (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 (H).

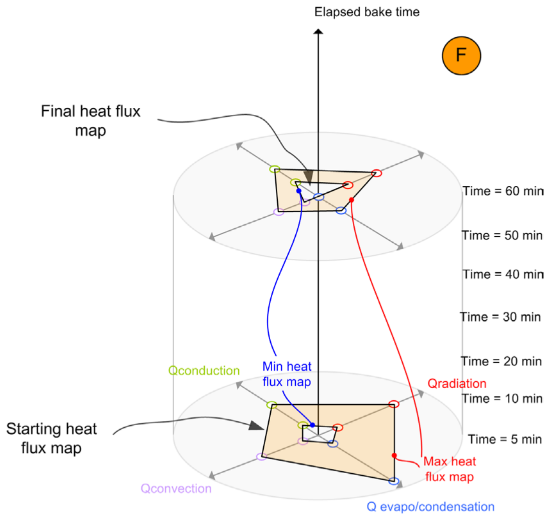

Figure 9. Feasible heat flux map that would give a satisfactory (edible) product

This volume (mountain shape) Fig. 10 (H) represents the BCZ for a particular product. The research challenge is to optimise this volume for the product under study and identify acceptable tolerance bands. Within this example, the bake time can vary from 30 to 40 minutes. The closer the heat flux map is to the top of the BCZ the longer the bake time. The ideal product is usualy that which has similar characteristics to the benchmark

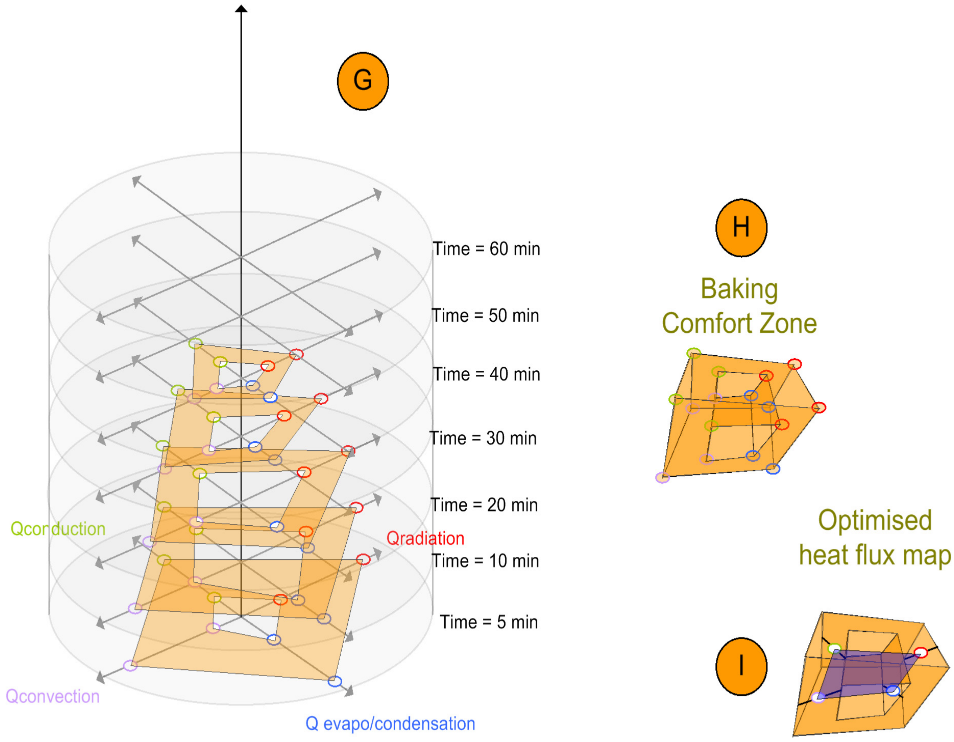

Figure 10. Concept of Baking Comfort Zone

product in the BCZ but the minimum bake time.

The product baked in these optimised conditions can be defined by the oven settings within the imaginary optimised BCZ represented by the volume represented by Fig. 10 (H).

If the heat fluxes to the product could be measured easily 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 heat transfer BCZ profiles for any baking product could be established either by experimentation (Design of Experiments techniques [40], [41]) or by a more sophisticated feedback control system for example using the Qualivision system (online colour an shape monitoring [42]) and an appropriate control algorithm (such as fuzzy logic). This way, BCZ profiles for any baking 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 optimised reference..

To estimate the optimised BCZ, hence the best heat flux path, it is important to relate the process variable changes (heat fluxes) to product response changes such as colour, crumb moisture, height, etc. The optimised heat flux map Fig. 10 (J) is considered to be optimised 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, 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 optimised product.

To optimise 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 experimentations to see if a greater input by one flux is a good method, or whether two or more fluxes need to be increased to achieve a reduced bake time.

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. In any experiment, measurements must be reliable and repeatable in any conditions. Product surface temperature remains a measurement challenge and cannot be measured repeatedly. As yet, the BCZ is difficult to apply in practice, because of various measurement issues.

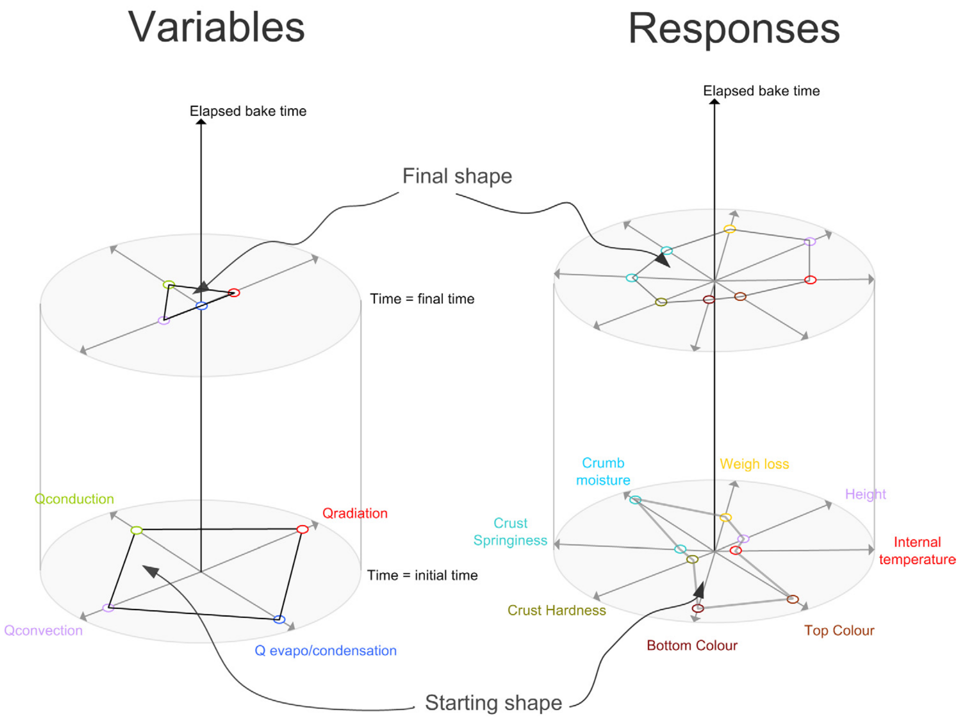

Figure 11. Process variables and product responses for the BCZ concept

4 Conclusion

This paper describes the baking 'comfort zone' concept, identifies heat flux maps and discusses their use for optimising the bake time of a cake product which has been the subject of a practical investigation with a high performance research oven.

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. On-line heat flux measurement for the product surface and an interface screen visualisation software system is presently under study.

ACKNOWLEDGEMENTS

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