

CHAPTER 8

Heat and mass transfer during baking

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Abstract

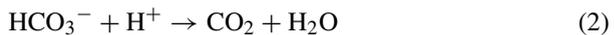
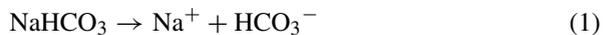
Located at the end of the processing line, baking is essential to the manufacturing of a variety of starchy foods (e.g. breads, cookies or biscuits, cakes). Baking is a very complex unit operation leading to products undergoing numerous physical, chemical and biochemical changes, such as water and fat phase transition, water evaporation, volume expansion, generation of a porous structure, denaturation of protein, gelatinization of starch, crust formation and browning reaction. These changes are appreciable involving products with typical macroscopic properties such as proper moisture content and product dimensions, desired and appealing color, texture and taste. As well, these will happen as a consequence of simultaneous heat and mass transfers within the product and with the environment inside the baking oven. Heat transport to the product will occur through radiation from oven walls and product surfaces, natural and forced convection from the movement of hot moist air, conduction from the carrier medium (e.g. mould, band) and within the product. Water transfer will occur through the evaporation of water from the product to the air and may also occur as a result of direct gas burning within the oven. Depending upon product characteristics and oven type, the relative contribution of the various mechanisms of heat transfer can be adjusted to influence the water transport in order to achieve a desired quality in the final product. Any attempt to modify or alter the process requires a thorough understanding of heat and mass transfer phenomena upon baking and their relationship with physical, chemical and biochemical changes involved. This chapter covers a general description of heat and mass transfers during baking and a review of mathematical modeling as applied to baking. It also discusses advances in the application of numerical methods in the description of heat and mass transport during baking.



1 Introduction

Baking is a very complex unit operation in which numerous physicochemical and biochemical changes take place within the starchy product. These happen as a consequence of heat (radiation, convection and conduction) and mass transfer (water vapor–air movement in the oven, water evaporation within the product and sometimes water generation by gas burning). Baking is not only performed to elevate the product temperature but also to induce some biochemical reactions of ingredients. During the temperature rise, some reactions are desired and some are inflicted. Overall the reactions render the bakery products more palatable and easily digestible. Baking will also structure the product and allow for the development of desired flavor and color. By the application of direct heat, baking will inactivate enzymes and various microorganisms. Induced by heat, baking will generate a significant decrease of the product's water content. Both phenomena will result in an appreciable increase of the starchy product shelf life. Undesirable transformations may also occur such as excessive browning, pigments and vitamins degradation and fat oxidation or rancidity as well as a general decrease of nutritional qualities by reversible or irreversible degradation of proteins. The challenge of baking is to manage over time the multiple desired and inflicted reactions as well as the heterogeneity of raw materials and final products. Often, it is highly desirable to obtain a gradient of final product properties from the surface to the core. The magnitude of various reactions will depend on the history or time dependency of temperature, moisture content and other variables (e.g. pH, water activity).

One of the most important changes is the product evolving from a liquid batter or semi-viscous dough to a solid alveolar structure at the end of baking. Products are characterized by two macroscopic phases with discontinuities. As a result of the elevation of temperature, fat melts (30–40°C) generating a decrease of batter or dough viscosity for further spreading. As well, partial gelatinization will occur at 60°C and coagulation at 90°C. Marcotte *et al.* [1] demonstrated that cake ingredients will shift the gelatinization of starch significantly from 60°C to almost 94–97°C due to the presence of cosolutes. Finally, gluten (80% of the protein content) will denature at 70–86°C. A significant volume expansion (2–5 times) occurs as a result of the significant production of the CO₂ from the added chemical leavening agent:



or from the yeast fermentation (before or during baking) assuming Y as an alcoholic fermentation agent and B as a lactic fermentation agent and z is the substrate:



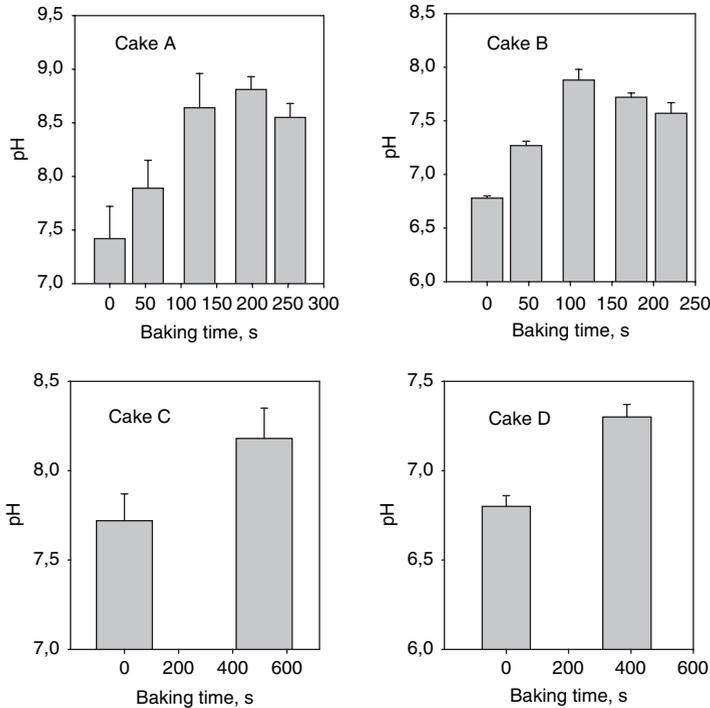


Figure 1: Evolution of the pH of starchy products during baking.

The chemical reaction of the leavening can be monitored indirectly through the measurement of pH of the baked product upon baking [2]. Hydrogen ion reacted with the bicarbonate ion in a straightforward way to produce water and carbon dioxide. The carbon dioxide migrates to gas nuclei in the batter and expands as it is heated, increasing the volume of the baking product. Figure 1 shows the pH evolution of four types of cakes during baking.

When baking starts, H^+ concentration decreases in the batter (pH increasing factor), producing CO_2 for volume expansion. At the same time, because of the water loss, H^+ concentration can increase (pH decreasing factor), since in the range of pK_1 (6.34) of bicarbonate solution, pH can move from a basic region to an acid region due to its concentration [3]. It might be inferred that in the earlier part of baking, the effect of the leavening reaction on pH is more important than that of the water loss. After the completion of the CO_2 release, its reaction rate decreased and the effect of water loss becomes a predominant factor for the later part of the baking, resulting in a decrease in pH. For bread baking, reactions will mostly take place during proving.

Air bubbles, introduced during the mixing of ingredients expand within the product during cake baking and contribute also to the volume expansion although to a lesser extent. Finally, upon baking the water evaporation/condensation within the

product structure results in a significant moisture loss qualified as moderate drying. Another important reaction influencing the quality of baked product is the appropriate brown color development on the surface by sugar caramelization, Maillard reactions, starch dextrination and/roasting of protein network.

In traditional baking, heat is supplied directly either by electrical resistance (e.g. wire, rods, tubes, plates) or by fabricated either in metal, ceramic-metal alloys or nonmetallic materials. Alternatively, gas burners may be installed in the baking chamber for direct heat. Because of gas combustion, CO₂ and water are being produced continuously enriching the air of the baking chamber. Periodically, these gas combustion products need to be evacuated. Indirect heat necessitates the presence of a combustion chamber apart from the baking chamber. Starchy products are either baked in batches or continuously. In batch baking process, products are entered. A time cycle of air temperature, velocity and humidity is applied. At the end of baking, products are taken out from the oven. Continuous baking processes are characterized by the movement of products along the oven. The oven is operated at steady state. The applied profile of air temperature, velocity and humidity vary along the oven length. Tunnel ovens are commonly used continuous oven type in the starchy product baking industry mainly because these meets the bakers' requests for increased mass production. The efficiency of energy utilization in a tunnel-type multizone baking oven is relatively high such as 50–70% for gas and 60–70% for electric ovens. As shown in Fig. 2, tunnel ovens are characterized by top and bottom baking chambers divided into several zones along the oven length. In each zone the temperature of the upper and lower baking chamber can be independently controlled so the application of an optimal temperature sequence is possible [4].

In most ovens, heat is transferred essentially by radiation. The air movement is induced by chimneys and natural convection. In a typical oven, heat transfer is influenced by the size, geometry, heating mode and wall properties of the oven, as well as by the size, geometry and physical, thermal and mass properties of baked products.

Typically, industrial baking cycles are established using a trial and error approach (at laboratory and industrial level) without a thorough understanding of the process. Often many adjustments are necessary requiring time and considerable amount of raw materials and generation of products with defects. As in drying, baking is a combination of heat and mass transfer. The knowledge of heat and mass transfer modes within the product and between the product and its environment and of the reaction kinetics as influenced by temperature and moisture content are crucial to properly and efficiently control this operation. The presence of volcanos, a major defect in cake baking, may result from an insufficient understanding of the phenomena as shown in Fig. 3.

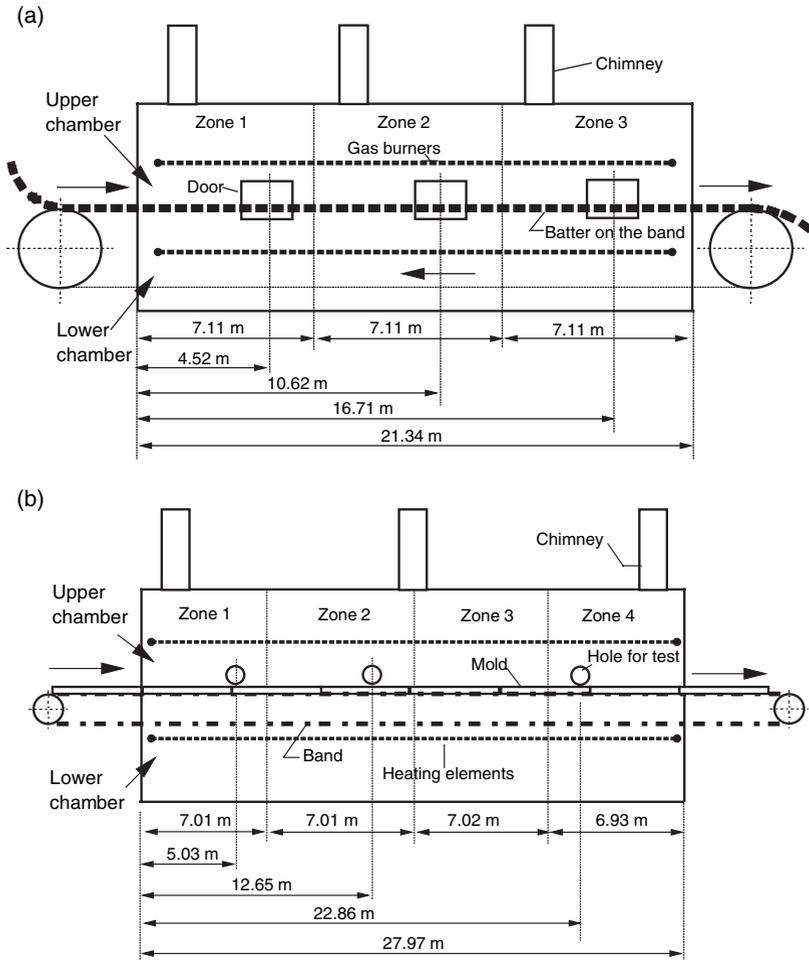


Figure 2: Schematic of two typical tunnel-type industrial baking ovens. (a) Gas fired band oven and (b) electric fired mold oven.

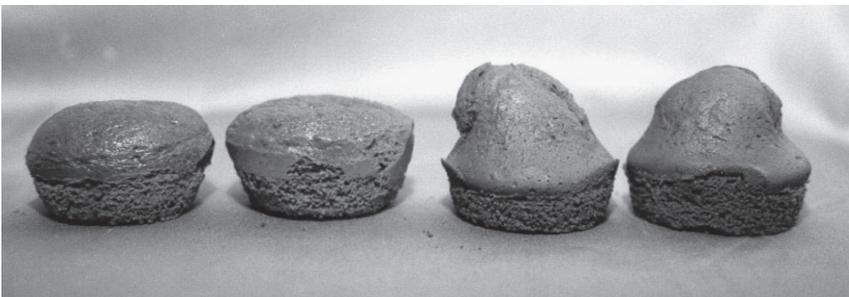


Figure 3: Generation of volcanos during baking of cup cakes.

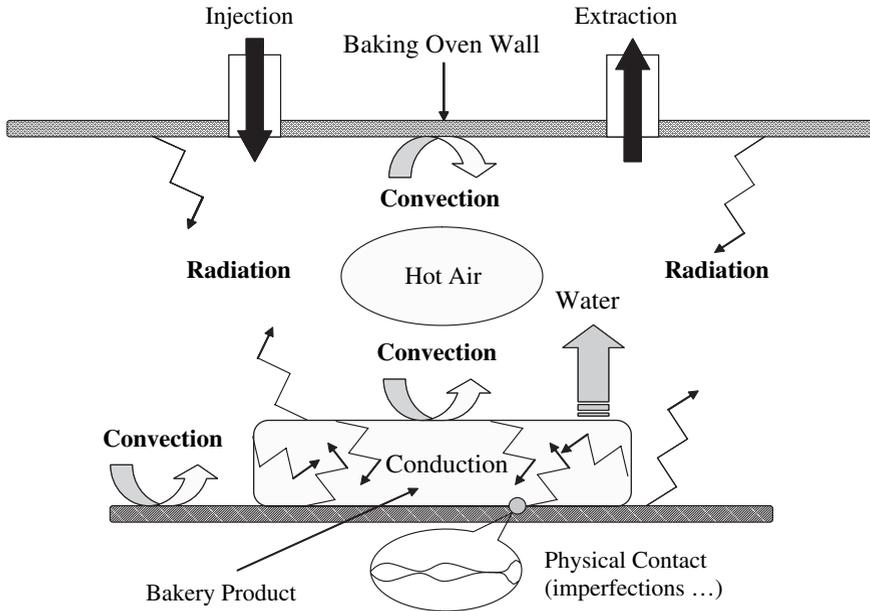


Figure 4: Heat and mass transfer phenomena.

2 Heat and mass transfer in the baking oven and within product

2.1 General description

Figure 4 shows heat and mass transfer phenomena encountered during baking. Heat is transferred by radiation from the oven walls to the product surface, by convection from the heating media (hot air and moisture) and by conduction from the surface of the carrier to the product geometrical center. At the same time, moisture diffuses outward to the product surface.

2.1.1 Radiation

Numerous studies were undertaken to study the contribution of individual heat transfer modes [5–10] for bread, biscuits and cakes upon baking in electrically powered, forced convection or gas fired ovens. Most studies revealed that radiation was the predominant mode of heat transfer for a proportion varying between 50% and 80% with respect to the total heat transfer.

Radiation is the transfer of energy by electromagnetic waves. All bodies emit electromagnetic waves at wavelength between 0 and infinity. Radiant energy travels uninterrupted until it strikes a surface where it is absorbed, reflected or transmitted. Radiant energy is transmitted through electromagnetic waves and is released after impacting a contact surface, converting into heat. It is only the absorbed fraction between 0.1 and 100 μm that is susceptible to be converted into thermal energy.

Radiation is an exchange of energy between two surfaces at two different temperatures without contact and transfer medium via emission, reflection and absorption of thermal radiation. Infrared energy is supplied in baking and roasting operations from the gas burners or electric elements as well as oven walls of ovens. Infrared energy is emitted by all hot objects. The radiation gives up energy to heat materials when it is absorbed. The rate of heat transfer will depend on (1) surface temperatures of the heating and receiving materials, (2) the surface properties of the two materials and (3) the shape of the emitting and receiving bodies. The amount of heat emitted from a perfect radiator (black body) is calculated using the Stefan–Boltzmann equation:

$$Q_r = \sigma AT^4 \quad (6)$$

where σ is the Stefan–Boltzmann constant and A is the area. Radiant heaters are not perfect. To take this into account, the concept of gray bodies is used and the equation is modified accordingly:

$$Q_r = \varepsilon \sigma AT^4 \quad (7)$$

where ε is the emissivity of the gray body (scale from 0 to 1). For most food products, the emissivity is equal to the absorptivity. The net heat transfer by radiation to a food is determined by

$$Q_r = \varepsilon \sigma A(T_1^4 - T_2^4) \quad (8)$$

where T_1 is the temperature of the emitting body surface and T_2 is the temperature of the food sample. In the context of baking, when using this relation, a lot of assumptions have been made. The area of product surface is assumed negligible in comparison to the walls area. Humid air is assumed transparent to radiation. The product surface and wall have ‘ideal’ optical properties (absorption and emission properties independent of radiation wavelength and direction). The exchange of energy is influenced by the respective dimensions of emitting surfaces and their relative position. A view factor is defined as the fraction of energy emitted by surface A_1 to be intercepted by surface A_2 . Abacus, diagrams and formulas exist for standard arrangements of surfaces [11, 12].

In their study on cake baking, Baik *et al.* [6] have used the following formula to calculate the proportion of heat transfer by radiation from the total heat transfer:

$$Q_r = \frac{\sigma(T_{kw}^4 - T_{kps}^4)}{\frac{1-\varepsilon_{ps}}{A_{ps}\varepsilon_{ps}} + \frac{1}{A_{ps}F_{psw}} + \frac{1-\varepsilon_w}{A_w\varepsilon_w}} \quad (9)$$

where, Q_r is the radiative heat, W ; T_{kw} , T_{kps} are the temperatures of the inner wall and the product surface in kelvin; σ is the Stefan–Boltzmann constant, $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$; ε is the emissivity and A is the area, m^2 . Subscript ps and w are the product surface and wall, respectively. F is a view factor between the product surface and the inner wall.



2.1.2 Convection

Convection heat transfer is a result of the movement of molecules or particles either by density gradients set up by temperature differences or by forced movement of the particles by external means such as a fan. Room heating by radiators or the stove top heating of water in a container are common examples of natural convection heating. Forced circulation of air using fans as in the case of baking chambers is an example of forced convection where turbulence is set in to facilitate faster heat exchange. Convection is governed by Newton's law which states that the rate of convective heat transfer is proportional to the surface area of heat transfer and the temperature difference between the surface and the fluid:

$$Q_{cv} = hA(T_s - T) \quad (10)$$

where Q_{cv} is the heat transfer by convection, h is the heat transfer coefficient, T_s is the product surface temperature and T is the temperature of the bulk fluid. The heating characteristics by convection may be very different in agitated systems (forced convection) compared to nonagitating systems (natural convection). Heat transfer by natural or free convection (involving a motion in a fluid) is due to differences in density and the action of gravity that causes a natural circulation and a heat transfer. For many problems, the superimposed effect of natural convection is negligibly small especially if forced convection exists. When there is no forced velocity of the fluid, the heat is transferred entirely by natural convection. In such cases, it is often necessary to consider also the radiation effect. Heat transfer by forced convection occurs with a moving fluid and a solid surface. The various kinds of forced convection, such as flow in a tube, flow across a tube and flow across a flat plate may be solved mathematically under certain assumptions regarding the boundary conditions. The essential step in the solution of the forced convection heat transfer is to determine whether the boundary layer is laminar or turbulent. Since heat transfer by convection involves both energy transfer and fluid flow, it defies rigorous analysis to a great extent. Because it is extremely important, procedures for the engineering analysis and modeling have been developed using empirical methods. It is important to have some means of predicting whether the flow would be laminar or turbulent in a given situation. In the laminar boundary layer, the fluid motion is highly ordered and it is possible to identify streamlines along which particles move. In the turbulent region, the motion is irregular and is characterized by velocity fluctuations which begin to develop in the transition region. These enhance the transfer of momentum, heat and species, and increase surface friction as well as convection transfer rates. The problem is solved by finding a way to use four variables: viscosity, density, velocity and diameter to characterize the flow independent of the dimensions. The resulting dimensionless number is represented by the symbol Re:

$$\text{Reynolds number } Re = \frac{Lv\rho}{\mu} \quad (11)$$

With respect to the type of flow, it is generally recognized that the flow is laminar if $Re < 2100$ in tube flow. There is a transition period from $2100 < Re < 4000$. Turbulence can usually be well established for $Re > 4000$. For an external flow on a flat



plate, the transition varies from 10^5 to 3×10^6 . The surface heat transfer coefficient is related to the physical properties of a fluid, gravity, temperature difference and the length or diameter of the container under investigation. The formulae that relate these factors are expressed as dimensionless numbers:

$$\text{Nusselt number} \quad \text{Nu} = \frac{hL}{k} \quad (12)$$

$$\text{Prandtl number} \quad \text{Pr} = \frac{C_p \mu}{k} \quad (13)$$

$$\text{Grashof number} \quad \text{Gr} = \frac{L^3 \rho^2 g \beta \Delta T}{\mu^2} \quad (14)$$

For the purpose of determination of the heat transfer coefficient in forced convection systems, the Nusselt–Reynolds correlations may be used. Instead of Reynold (Re) number, the Grashof (Gr) number is used for natural convection problems. Heat transfer through air is lower than through liquids. Larger heat exchangers are needed when air is used and higher rates of heat transfer are obtained by moving air. Condensing steam produces higher rates of heat transfer than hot water and the presence of air in steam reduces the rate of heat transfer.

Specifically in baking, there are three common equations for the calculation of heat transfer coefficients. For laminar flow to flat plate [13], the following equation is used to approximate the heat transfer by convection:

$$\text{Nu} = 0.664 \text{Re}^{1/2} \text{Pr}^{1/3} \quad (15)$$

The second equation is based on an equivalent diameter approach used for a pilot scale conveyor biscuit oven [14]. The equivalent diameter is calculated as follows:

$$D_{\text{eq}} = \frac{2bH}{(b+H)} \quad (16)$$

where b is the width and H is the height of the baking chamber, and Reynolds number:

$$\text{Re} = \frac{VD_{\text{eq}}}{\nu} \quad (17)$$

and the Nusselt number (valid for $\text{Re} > 40$):

$$\text{Nu} = 0.7 \text{Re}^{0.61} \quad (18)$$

The third equation is a practical correlation applied for cooling and heating by air flow over flat surfaces [15] (valid for $\nu < 0.5$ m/s):

$$h_c = 5.7 + 3.9\nu \quad (19)$$

A prediction equation for natural convection can be used as well, since the air velocity range in a typical industrial oven is low and sometimes falls within the category of mixed forced and natural convection [16]:

$$\text{Nu} = 0.82(\text{GrPr})^{1/5} \text{Pr}^{0.034} \quad (20)$$



The idea is to estimate the heat transfer coefficients using a hypothetical forced correction. If values are lower than those obtained for natural convection, values for natural convection heat transfer coefficients are recommended.

2.1.2.1 Thermal boundary layer. In a typical baking oven, the thermal boundary layer is considered as an insulating layer which resists heat flow between the air mass and the product surface. This boundary layer has different properties and a different velocity from the main fluid mass [17]. Since the convective heat transfer coefficient is normally defined based on air mass temperature outside the boundary layer, in order to calculate the heat transfer coefficient, the air temperature outside the boundary layer must be known. An easy way to determine is to position various thermocouples at different heights from the surface of the product. Baik *et al.* [5] demonstrated that in a typical baking oven for snack cakes where the distance between the heating element and the product would be 200 mm and velocities lower than 0.5 m/s, the boundary layer would be between 40 and 50 mm over the product.

2.1.3 Boiling heat transfer

If a phase change process takes place as during boiling, the heat transfer coefficient is much more complicated than for single phase convection. Four regions can be distinguished. In pooled boiling, at low temperature gradient, very few bubbles are formed and released, and the heat transfer is similar to natural convection in a liquid. During nucleate boiling, the rate of bubble production increases enhancing the circulation of the liquid and therefore increasing the heat transfer coefficient. During film boiling the bubbles are formed so rapidly that they join to form a film of vapor between the surface and the liquid. It forms an insulating layer and decreases the rate of heat transfer. With a very large temperature gradient, the heat transfer can occur due to radiation. Boiling heat transfer can be an important phenomenon within the product during baking as water evaporates.

2.1.4 Condensation heat transfer

Condensation occurs when saturated vapor comes into contact with a colder surface. The liquid collects on the surface and is removed either by gravity or carried away by the moving vapor. Two modes of condensation may be encountered. The most common is film condensation and it occurs when a film of liquid is formed over the entire surface. Drop-wise condensation occurs on nonwetable or contaminated surfaces. A portion of the surface is in direct contact with the surface making heat transfer rates much higher than for film condensation. These principles are used to design evaporators. Upon the migration of the evaporated water within the product during baking, condensation is likely to occur.

2.1.5 Experimental proportion of radiation and convection

Heat flux (W) or heat flux densities (W/m^2) were found to be the best nonintrusive indicator or metric to characterize the performance of ovens with respect to the product upon baking. They are measured directly in the oven using commercially available heat flux sensors. It is based on the assumption that the heat transfer



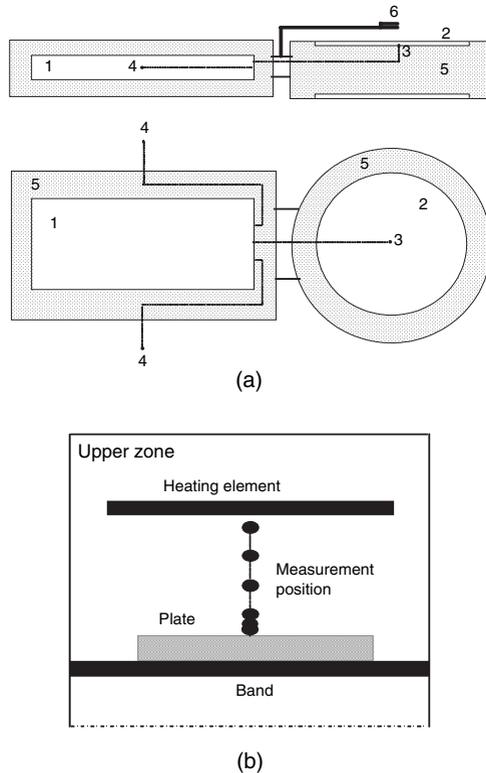


Figure 5: (a) Simplified description of h-monitor and (b) measurement position inside the baking chamber of the tunnel-type multizone industrial oven tested. (1) SMOLE, (2) aluminum plate, (3) thermocouple for plate temperature, (4) the original (manufacturer) thermocouple position for air-mass temperature, (5) insulation, and (6) thermocouple holder for air temperature measurement.

between the oven and the dough/batter is the same as between the oven and the sensor. However, one must always remember that there are differences in surface properties and temperatures experienced by the starchy product and the sensor. Figure 5 shows a typical heat flux sensor used commonly for total heat flux measurement.

Camden and Chorleywood Food Research Association (CCFRA) in the UK were probably the first to report on the development of a heat flux probe allowing the measurement of the actual heat flux (W/m^2) to a product upon baking. Using a pilot-scale forced convection oven, research conducted by Fearn *et al.* [18] established linear relationships between heat fluxes and biscuits properties, for a wide range of air velocity and temperature. De Vries *et al.* [19] demonstrated the power of the measurement of heat fluxes to monitor and to control the baking process. They

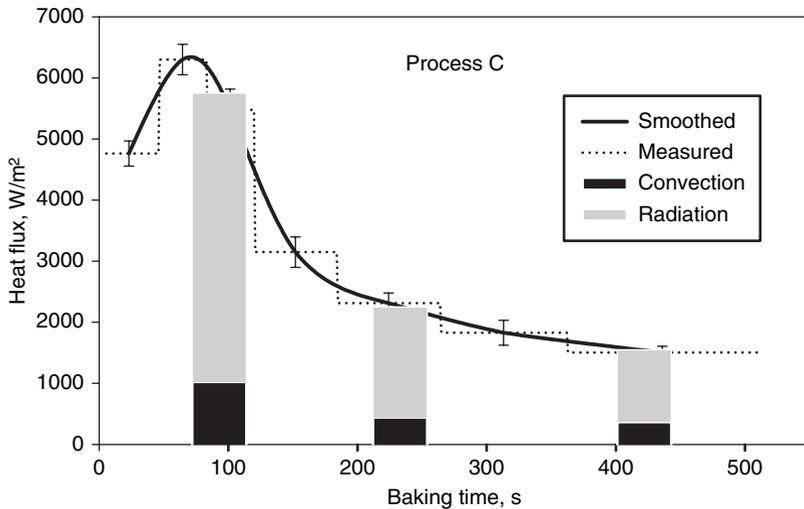


Figure 6: Relative proportion of heat transfer by radiation and convection.

suggested that a 10% reduction in energy consumption was possible, optimizing the performance of baking ovens through the application of a heat flux approach. Heat fluxes were found to be dependent on air temperature and velocity. Linear relationships were established between oven conditions and biscuits properties and oven settings and heat fluxes and power use. Li and Walker [20] measured the oven heat transfer rates during cake baked in conventional, impingement and hybrid ovens and reported average values of apparent convective heat transfer coefficients using a h-monitor in commercial conveyor ovens. Under constant baking conditions of an experimental oven kept at 300°C without forced convection and an air flow of 1 m/s, total heat fluxes were reported constant at 8000–19,000 W/m² [19]. As shown in Fig. 6, Baik *et al.* (1999b) [5] used the h-monitor device to evaluate heat transfer coefficient on commercial cake in a tunnel-type electrical industrial oven. At the beginning of the process, surface heat flux increased to around 6300 W/m² and then decreased quickly to 2500 W/m² and slowly. A similar pattern was reported for another type of cake but the maximum value was 7550 W/m². It then decreased smoothly to 1570 W/m² and increased slightly to 1950 W/m². Figure 6 shows that a significant proportion of heat transfer was coming from radiation. These values were much higher than the 1700 W/m² to 2000 W/m² measured in a tunnel-type biscuit oven operated at 200°C with 1–3 m/s of air velocity [8] or 1200 W/m² to 900 W/m² (slightly decreasing) for indirect fired experimental oven kept at constant 220°C with 0.6 m/s [7].

2.1.6 Conduction

Conduction heat transfer occurs in solid bodies and is transmitted directly through molecules. The rate of heat transferred by conduction is determined by the temperature difference between the food and the heating/cooling medium and the total

resistance to heat transfer. Fourier's law of heat conduction states that the heat transfer rate through a uniform material is directly proportional to the area of heat transfer and the temperature gradient with reference to the thickness in the direction of heat transfer. Mathematically, for 1D heat transfer:

$$\frac{dQ_c}{dt} = -kA \frac{dT}{dx} \quad (21)$$

where dQ_c/dt is the rate of heat transfer, A is area of heat transfer, dT/dx is the temperature gradient across unit thickness and k is the proportionality constant (thermal conductivity). A negative sign is included on the right-hand side because dT/dx is negative (temperature decreases as thickness increases).

If the temperature at a given point within the food during processing depends on the time of heating or cooling and the position within the food, unsteady-state conduction conditions prevail. Temperature changes with time and directions result in equations that are more complicated. The governing partial differential equation for unsteady-state conduction heating involving a 3D body is given by

$$\frac{\partial T}{\partial t} = \alpha \left[\left(\frac{\partial^2 T}{\partial x^2} \right) + \left(\frac{\partial^2 T}{\partial y^2} \right) + \left(\frac{\partial^2 T}{\partial z^2} \right) \right] \quad (22)$$

The assumptions associated with the above equation are (1) the product temperature is uniform at the start of heating, (2) the surface temperature of the 3D body is constant after the start of heating and (3) the product thermal diffusivity α is constant with time, temperature and position in the body. The differential equation can be solved analytically for simple shapes (cylinders, slab or sphere). For complex geometries or for thermal properties that vary as a function of the position within the food, numerical methods are needed to solve these equations.

Evidence of a significant heat transfer by conduction can be easily demonstrated while baking starch products in moulds. Figure 7 exhibits cup cakes that were taken out before the end of baking. The core structure collapsed and a layer of cooked solid product was found from the mould surface to the core of the product.

Baik *et al.* [6] have calculated the approximated proportion of individual heat transfer (radiation, convection, conduction) for two tunnel-type baking ovens (electrically operated and gas fired) and four types of products. Figure 8 shows that the heat transfer to the top surface (Q_s) occupied 20.2–56.2% of the total heat in both ovens. Radiation was the predominant heat transfer mode (79.5% and 81.5%) for the top surface of cakes in the gas oven. Using the electric oven 66.2% and 72.4% of the total top surface heat transfer was provided by radiation. If the radiation heat from the heating element was taken into consideration, a higher ratio of radiation could be observed. In addition, the assumption of the average conditions and the uniform radiation transfer across the oven length could cause some deviations. The conduction ratio to total heat was higher in the electric mould oven (79.8% and 78.1%) than in the gas oven (43.7% and 49.0%). The area of the exposed surface receiving radiation and convective heat was smaller than that in the gas oven.

A thorough understanding of the heat transfer mechanisms make possible to adjust heat fluxes from bottom and top chambers of various types of ovens in order



Figure 7: Evidence of conduction heating within cup cake during baking.

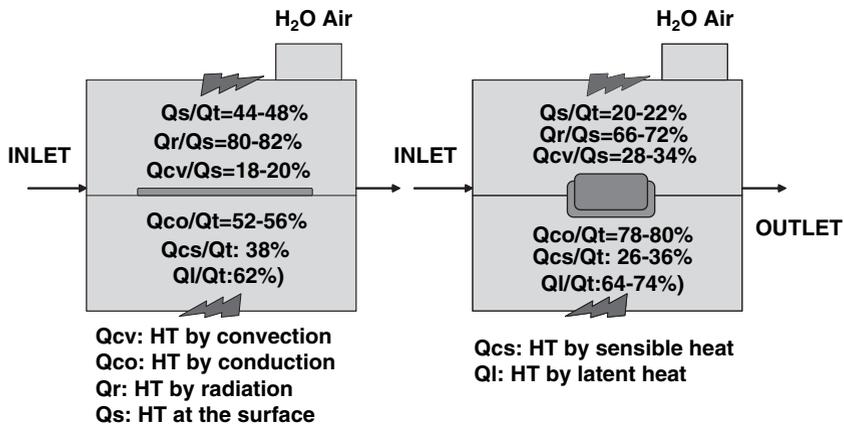


Figure 8: Relative proportion of heat transfer by radiation, convection and conduction.

to avoid the generation of major defects. Zareifard *et al.* [21] developed a method to balance heat fluxes for a newly designed pilot oven aiming at representing continuous baking conditions of various tunnel-type industrial ovens. In their process for validation of the pilot oven heat fluxes, they found that as the total heat flux from the top and the bottom chambers were closer to the total industrial heat flux, the proportion of volcanos was decreased exponentially as shown in Figure 9.

Zareifard *et al.* [21] also identified that heat flux sensors were limited in detecting heating heterogeneity at 5% difference within the location in the baking ovens. To obtain uniform baked cakes, differences of 2–4% were necessary. Starchy products were found to be highly sensitive to heat fluxes.

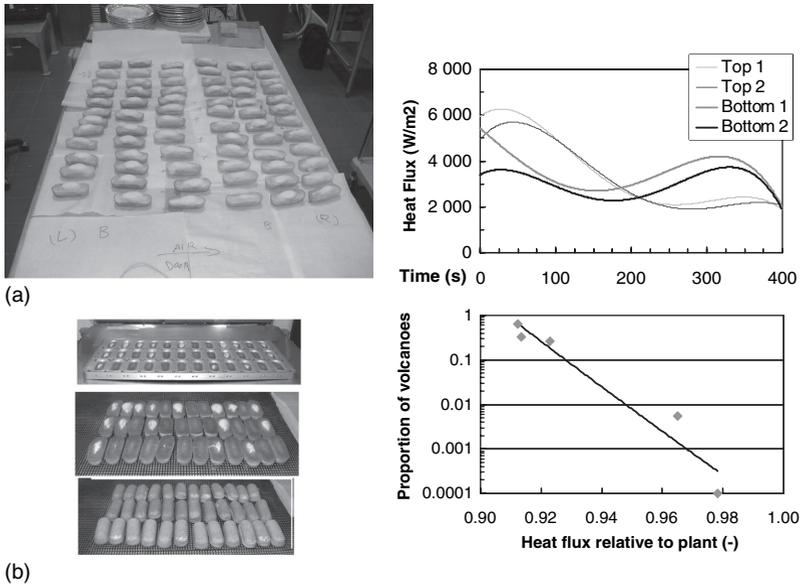


Figure 9: Adjustment of the heating profiles for bottom and top chambers to prevent the generation of volcanos: (a) high proportion of volcanos and (b) low proportion of volcanos.

2.1.7 Moisture distribution within product

The initial moisture content of starchy products is a result of water addition at the dough mixing stage together with water naturally present in some ingredients. As shown in Fig. 10, moisture contents, expressed on a dry basis, were found to decrease linearly as a function of baking time which would tend to indicate that drying rate were constant. However, it cannot be clearly stated that no falling rate existed since the air temperature and humidity were variable during baking and only point measurements were performed. The rate of drying may be one of comparative parameters in the baking process. In the case of cookie baking [22] in a continuous oven (160–200°C), the constant drying rate period seemed to occupy around 40% of the whole baking process. The drying rate was about 1.82×10^{-3} kg H₂O/kg solid s (estimated from the data in the graph). During bread baking in an electric batch oven (200°C), the drying rate varied from 2.78×10^{-5} to 2.36×10^{-4} kg H₂O/kg solid s [23]. Baik *et al.* [2] found that magnitudes of the drying rate of cakes (4.677×10^{-4} kg H₂O/kg solid s to 1.395×10^{-3} kg H₂O/kg solid s) fell between those of cookie (typical final moisture content: ~4%) and bread (~35%).

2.1.8 Simultaneous modeling of temperature and moisture distribution within product

It is generally recognized [24] that the temperature and moisture distribution within the product can be predicted using the following heat and water diffusion equations:

$$\text{Heat diffusion} \quad \rho_b C_{pb} \frac{\partial T}{\partial t} = \nabla(k_p \nabla T) + \rho_l \lambda_v \frac{\partial C}{\partial t} \quad (23)$$



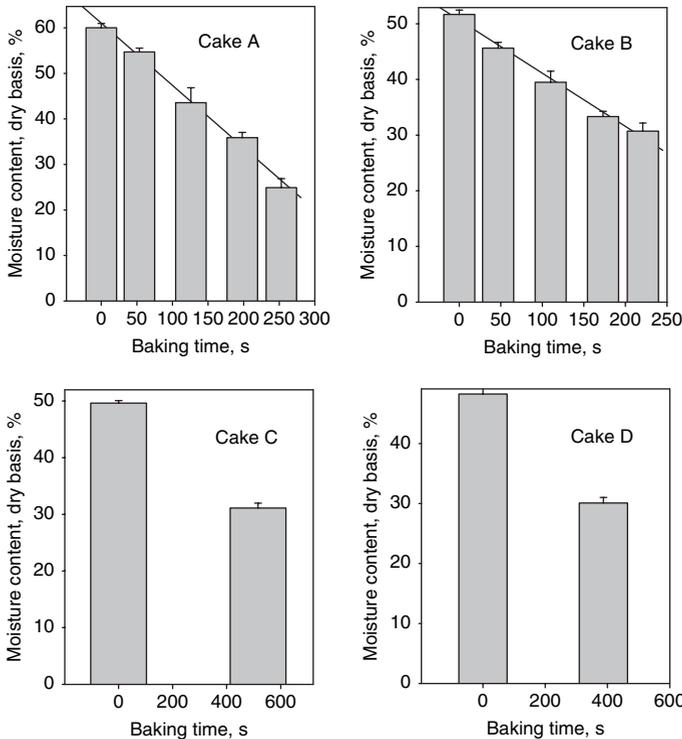


Figure 10: Evolution of moisture content within the cake during baking.

$$\text{Water diffusion } \frac{\partial C}{\partial t} = \nabla(D\nabla C) + \alpha_1(\nabla T) \quad (24)$$

with boundary conditions

$$k_p \nabla T \cdot n = h_t(T_a - T_s) \quad (25)$$

$$D\nabla C \cdot n = h_m(C_a - C_s) \quad (26)$$

$$k_n \nabla T \cdot n = \varepsilon \sigma (T_{kw}^4 - T_{ks}^4) \quad (27)$$

The heat and water diffusion equations are coupled through the second term of the right side of eqns (1) and (2) and must be solved simultaneously. To predict temperature and water distributions within the product during baking knowledge of product properties such as bulk density, heat capacity, thermal conductivity, effective moisture diffusivity is necessary. Because product properties are temperature and water dependent, the resulting system of equations is nonlinear and the solution procedure is more complex. It is also necessary to obtain accurate values of the latent heat of evaporation and convective heat and water transfer coefficients. Since the radiation heat transfer is predominant, values of absorption coefficient of product, oven surfaces and air/steam mixtures are required. To obtain transient temperature

and water distribution in the product, nonlinear partial differential equations with appropriate initial and boundary condition have to be solved using numerical methods (e.g. finite difference or finite element). In addition, heat and water transport analysis of the baking chamber requires solution of 3D conservation equations for mass momentum, energy and water.

3 Physical, thermal and mass transfer properties

3.1 Thermophysical properties

Heat capacity, thermal conductivity, thermal diffusivity and density are regarded as key thermophysical properties for modeling of heat transfers during baking as well as to design baking ovens. Information regarding thermophysical properties of batter, dough and bakery products is scarce in the literature and usually not available at various temperature, moisture and density levels. Until now, many researchers have measured thermophysical properties with various measurement techniques that are found in the literature. Rask [25] reviewed data and prediction models of thermal properties of bakery products. Lind [26] presented measurement techniques and models for thermal properties of dough during freezing and thawing. Traditionally, properties were measured on bread products but recent studies focused more on other starchy products. Baik *et al.* [27] measured thermophysical properties as affected by cake baking conditions and volume expansion and observed a combined effect of moisture content, temperature and density on thermal properties. The interaction between moisture content and density was significant for thermal conductivity as was the interaction between temperature and moisture content on specific heat. They found discrepancies between predicted and experimental values, especially for thermal conductivities that are greatly influenced by the porosity of the starchy product. More recently, Baik *et al.* [28] reviewed common and new measurement techniques, prediction models and published data on thermal and physical properties of bakery products. Even though several modeling approaches have been proposed to predict thermal properties of a material at desired conditions, none of them can be used over a wide range of foods [29]. The most promising approach is based on chemical composition, temperature and physical characteristics. A general expression of series model gives the thermal property of foods as a function of the thermal property of its components [30]. This has been applied successfully for specific heat, density and thermal diffusivity of bakery products, considered as a porous material. For the prediction of thermal conductivity of porous food, a theoretical argument favors the use of a parallel structural model (two phases: continuous and discontinuous) or the use of the Maxwell–Eucken model. Other structural models include the Kopelman, the Kee, the fluid continuous, the solid continuous, the combined parallel–perpendicular and the random distribution. In their evaluation of nine different structural models, Murakami and Okos [29] found that parallel and perpendicular models showed 12–97% and 18–61% standard errors. These models require empirical factors or product specific information not easily available in the literature. All structural models neglect



interactions between components and phase transitions which are significant in bakery manufacturing. Therefore, regression models based on experimental data are used more than structural models. Moreover, for bakery products, there is a significant volume increase to be included for the prediction of properties. A similar approach is used in drying where it has been demonstrated that it was important to take into account nonhomogeneous shrinkage to predict the drying of macroscopic phases. For bakery products, the mass fraction model (water and dry solid) was found to give satisfactory results for specific heat. However, predicted values are generally lower than experimental data, attributed to the binding of water within the structure. Due to the complexity of the mixing, proofing and baking processes in which chemical and physical reactions (e.g. phase transition of water) occur, the complicated temperature and water content history that are location dependent and the significant volume expansion of the whole structure, empirical models such as regressions or neural network approaches [31] are found to be more appropriate than structural models for the calculation of properties. Neural networks as a modeling technique have several advantages. First, these can relate the input and output variable without any prior knowledge of the relationship between them. Second, they can be used for modeling very complicated and nonlinear case with multiple input and output variables. Third, neural networks have much faster calculation speed than conventional mathematical modeling methods.

3.2 Mass diffusion and transfer properties

Compared to thermal properties, mass diffusivities of bakery products have been poorly studied. The moisture diffusivity within an expanding cake structure was studied by Baik and Marcotte [32]. Table 1 shows the resulting values of moisture diffusivities as a function of moisture content and porosity.

Moisture diffusivities for high porosity samples decreased with increasing moisture content. Those for low porosity samples increased with increasing moisture content while those for middle porosity samples rose and fell as moisture content increased. The porosity and moisture were inversely related. This was explained, at temperatures below 70–80°C, by the water migrating in a liquid state accompanied by liquid water diffusivities increasing with the water content. At higher temperatures, the porosity increased as a considerable amount of water was being generated. The water migrated both in the liquid and in the vapor state. Moving toward a greater amount of vapor, water diffusivity in a porous media was found to be directly proportional to the porosity, decreasing as the water content decreased.

Mass transfer coefficients can be estimated using the heat and mass transfer analogy which was applied to the modeling of biscuit baking in a tunnel baking oven [33]:

$$\frac{h_c}{h_m \lambda_v} = 64.7 \text{ kg/ms}^2 \text{ K} \quad (28)$$



Table 1: Effective moisture diffusivity $D_e \times 10^{10} \text{ m}^2$ of cake batter during baking.

	Relationship of temperature to the average porosity			
	Low $\varepsilon = 0.15-0.2$	Medium $\varepsilon = 0.35-0.5$	High $\varepsilon = 0.55-0.7$	High $\varepsilon = 0.7-0.8$
Average product temperature in the first falling rate period	33.1–35.9°C	53.5–58.5°C	73.8–84.1°C	118–126°C
M_o (d.b.)				
0.369	0.99±0.1	4.6±0.5	31±3	38±22
0.431	1.2±0.1	5.6±1.0	26±6	350±64
0.539	1.31±0.01	5.6±2.4	27±17	340±130
0.611	1.2±0.2	5.0±0.1	25±5	340±140
0.707	1.4±0.2	4.8±1.5	22±3	270±23

4 Starchy products as bubble foods or cellular solids

Starchy products belong to the broad category of ‘soft’ materials considered as man-made heterogeneous structures. These cellular solids comprised of a solid matrix and an associated fluid (mostly air) and contain more than one phase at macroscopic level. If the fluid is air, cellular solids have low densities. Cellular solids are alternatively named bubble foods. The constituents can retain their identity or interact with each other in various phases. Typically bakery products (e.g. breads, cookies, cakes) fall in this category because they are comprised of solid structures containing air giving them their desired or appealing textural properties.

The principles for studying the structure and properties of cellular solids were laid out by Gibson and Ashby [34] and by Weaire and Hutzler [35]. A relationship was established between the Young’s modulus (an indication of the hardness of the structure) and the density as well as between the failure stress and the density as

$$\frac{\varepsilon^*}{\varepsilon} = C_\varepsilon \left(\frac{\rho^*}{\rho} \right)^2 \quad \text{and}$$

$$\frac{\sigma^*}{\sigma} = C_\sigma \left(\frac{\rho^*}{\rho} \right)^{1.5} \quad (29)$$

where C is the parameter characterizing the microstructure, * indicates the property of the cellular solid whereas the absence of * indicates only the property of the solids without bubbles. At first, food technologists applied these principles to develop consistent strategies for creating and controlling cellularity in extruded starch foams [36]. Models were developed further to describe volume expansion in other areas of research [37], for extrudate expansion [38] and for bread [39]. To

demystify structure-property relationships of cereal products, Elmehdi *et al.* [40, 41] used the same principles. It is interesting to point out that the volume fraction occupied by gas bubbles in a final bread product may represent more than 50% of the total loaf volume [42]. However, the majority of the rheological studies on starchy products [43] have not viewed the presence of gas bubbles as an important area of investigation, despite their importance to the rheological properties of the processed dough/batter. Alternatively, Campbell *et al.* [44] are viewing starchy product making as a series of aeration stages with published detailed results on number, size and distribution of bubbles during the proofing of bread. In their recent study, Babin *et al.* [45] have shown that the Gibson and Ashby models could not explain satisfactorily the great dispersion of experimental data for extruded starches. The difference of mechanical properties for samples of same density could be explained by their inherent microstructure (number of bubbles, size and distribution).

It is well recognized in the literature that there is not only a strong relationship between the formulation (choice and quantity of ingredients) and final product properties but also between processing conditions and final product properties [2, 6]. Moreover, the properties are influenced by the structure that may be evolving during processing. Due to a lack of knowledge, most of the research on these relationships are specific to a particular operation and product, and the relationships are established using a trial and error approach. The processing of a typical bakery product requires several steps including using the appropriate flour (the major ingredient that may change from year to year due to varying weather conditions, origin of the grain, cultural practices, grain milling processes, etc.), adding other ingredients (e.g. sugar, fat, leavening agents, water) by mixing (incorporation of air), forming, proofing (e.g. bread fermentation for CO₂ production) and final baking (e.g. air temperature, humidity and velocity in various ovens, moisture evaporation within the product) at the industrial plant. Variations at any of these steps (e.g. flour grain production, milling factory, bakery plant) can affect one's ability to manufacture a bakery product of the final structure with desired macroscopic physical characteristics (e.g. consistent dimension, density, moisture content, surface color and texture). Industrial variability is experienced quite frequently (e.g. uncontrolled thickness of cookies, undesirable cake volcanos, textural variations making the resulting cookies more brittle and fragile, bread or cookie dough sticking to the equipment during the forming process). In a typical bakery plant, the control of the product yield (i.e. the ratio of a given mass of product to its volume) is compulsory. On the one hand, it is relatively easy to control the mass of product. This is performed on a routine basis as a quality control measurement. However, since the volume of a typical bakery product will expand significantly (4–10 times) upon processing (e.g. proofing, baking), controlling the volume expansion (i.e. the yield) still remains an important difficulty. Troubleshooting of these recurring variability problems is not an easy task and requires in-depth, hands-on practical experience. Because of a lack of basic understanding of the mechanisms involved, solutions are normally found empirically. This is quite time consuming and expensive (because of the quantity



of raw materials needed), and results in considerable product waste. Understanding the effect of ingredient selection and processing conditions on the resulting structure and properties during mixing, proofing and baking is a key issue.

4.1 Volume expansion kinetics

During baking, as the dough/batter of starchy products increased, the macroscopic volume is expanding from the effect of the air incorporation (mixing), the production of CO₂ either by the chemical agent or by fermentation (proofing) and the water vaporization (during baking). For all starchy products, typical kinetic profiles are usually obtained: an increase up to around two-thirds to two-fourths of the baking time then a decrease to some extent. As invasive measurements may provoke dough/batter collapsing, nondestructive or noninvasive methods are increasingly being used to elucidate the food structure to provide a better understanding of the nucleation and growth of bubbles. As an example, digital image analysis was used to classify various cellular structures of spongy cereal products [46]. Characterization of the microstructure of cereal-based foods as a function of moisture content has been recently achieved using Environmental Scanning Electron Microscopy (ESEM), allowing the examination of food samples for high water activity range in their natural state [47, 48]. More recently, X-ray tomography [45] was used to study the 3D structure with a high resolution without the need for sample preparation. Magnetic resonance imaging (MRI) [49, 50] has been successfully used to study the movement of water during proofing of bread in an attempt to assess the local porosity. More recently, MRI has been applied to study bubble expansion and growth in bread during baking [51]. Recently, low frequency ultrasounds (50 kHz) have been used successfully to monitor bread dough fermentation [40], to investigate the cellular structure of bread crumb [41]. More and more ultrasounds are seen as useful tools for investigating mechanical properties or structural characteristics or viscoelastic materials. Results reported in the literature are highly frequency dependent. The velocity has greater sensitivity to the presence of bubbles at low frequencies and to the properties of the dough matrix at high frequencies. Although for other field (e.g. polymer foams), there has been a great deal of development for online monitoring [52, 53], these transducers are still being adapted for online ultrasonic monitoring of batters and other food systems [54].

Figure 11 shows the volume expansion kinetics at various temperatures. A typical increase was observed to reach a maximum volume. Then the cake volume decreased significantly. The height of the cake as well as the rate of increase is greatly affected by the baking temperature. These profiles are typically obtained for other bakery products such as bread [55] or cookies and are even similar to those obtained for extruded products [38]. A visual observation of the baking process demonstrated that the volume expansion ceased as soon as there was a significant crust formation at the surface. As well, the viscous batter is gradually becoming an elastic cellular solid. Bubbles expansion is reduced by the solidification of the structure.



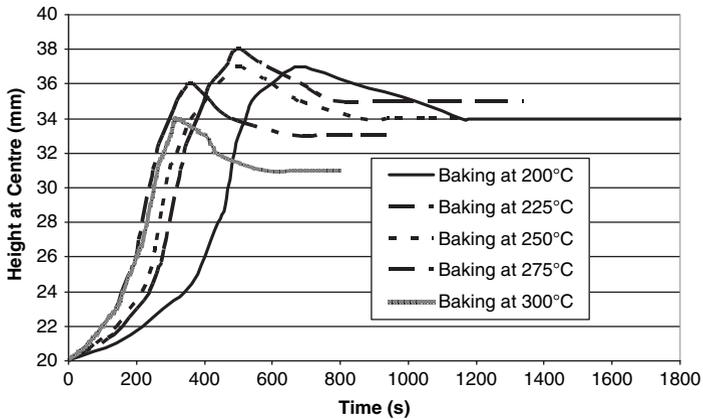


Figure 11: Volume expansion kinetics.

The shape of the curves in Fig. 11 is typically encountered for all bakery products although the magnitude of volume expansion or spread may change according to product formulations or recipes.

4.2 Modeling of volume expansion kinetics

It is well understood that volume expansion is necessary to create an aerated structure in the baked starchy products with desired characteristics of mouth feel, digestibility and softness, etc. Volume expansion is the result of gaseous expansion incorporated during mixing (expansion of air), yeast proving or chemical leavening reaction (CO_2 generation) and baking (water vapor generation). The driving force of the volume expansion phenomenon is the expansion of all individual bubbles within the structure due to the pressure difference between the inside and the outside of the bakery product. Volume expansion has been modeled using two distinct approaches either rheology or diffusion based. Using the rheology approach, the volume expansion results from an imposed pressure difference between the gas bubble and the surrounding liquid whereas in the diffusion-based methodology, volume expansion is governed by the rate of mass transfer of the diffusing species. New hybrid models combine both approaches. A 1D model for heat and mass transfer within a sponge cake batter during a baking process was developed by Lostie *et al.* [56]. This model took into account both the heat and mass transfers combined with the thickness change of cake during baking. Fan *et al.* [39] suggested a volume expansion model of dough during baking based on rheology whereas Shah *et al.* [57] developed a simplified model for the growth of individual bubbles in bread dough based on the mechanism of gas-liquid diffusion to describe the bubble growth. Although most studies on modeling concentrated on the description of either the heat or/and moisture transfer or volume expansion during baking only few reported on dealing with all combination of phenomena and that is necessary

to understand the volume expansion as affected by baking conditions and bakery product recipes. Various input data on properties varying with time and temperature is necessary to use these models. These are not necessarily easily measurable or even available in the literature. In reference to Fig. 11, it is generally well accepted that the first part of the graph is relatively easy to model whereas the second part is not very well understood. The understanding of volume expansion will remain for few years a very popular R&D subject.

5 Conclusions

Baking is crucial in determining the quality of flour-based foods. The quality factors of baked products include many aspects such as sponginess, flavor, texture, volume and browning. These quality factors or process outputs are varied with process input variables: oven temperature, moisture and process time.

The process of baking is complicated because it involves not only physical changes, such as temperature and moisture because of heat transfer and moisture transfer, but also chemical reactions to generate the desired final product quality, i.e. a typical bubble or aerated structure, a good flavor and an optimal color. In addition, most of material properties are dependent on baking conditions such as temperature, moisture and process time. It is hard to measure these properties under these conditions. Thus, it is still a challenging subject for food scientists to develop such a model which can simulate the baking process especially under conditions of a real baking system including baking oven and the food product.

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