Food Bioprocess Technol (2016) 9:664–674
DOI 10.1007/s11947-015-1660-3

ORIGINAL PAPER

Baking of Sponge Cake: Experimental Characterization and Mathematical Modelling

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Received: 22 June 2015 / Accepted: 9 December 2015 / Published online: 21 December 2015

Abstract Sponge cake is a sweet bakery product that begins as a fluid batter and, during baking, transforms into a porous solid, presenting an important volume expansion. The aim of this work was, first of all, to study experimentally the influence of operative conditions (natural and forced convection; oven temperature, from 140 to 180 °C; steam addition) on volume expansion and the heat transfer dynamics during baking of sponge cake. It was observed that an increase in oven temperature, airflow and steam injection produces an increase in volume expansion. Secondly, a mathematical model was developed to simulate heat transfer coupled with volume expansion. Both experimental and simulated temperature profiles verified that the last region to achieve a correct degree of baking is the one near the crust around the axial axis. In consequence, the minimal baking time was defined as the average time at which this region reaches 95–98 °C. The baking time was strongly affected by the effective oven temperature, with a slight influence of the convection mode.

Keywords Sponge cake · Volume expansion · Heat transfer simulation · Baking time

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Introduction

Currently, baking industries rely on a high-technology production chain in order to respond to an increasing and demanding market (Decock and Cappelle 2005). Innovation and research had been the key to achieve this goal. In this sense, a great number of studies have been made in order to understand more deeply the process and the changes which are responsible for the final product quality.

During the baking of sweet bakery products such as sponge cake, the product starts as a fluid batter and, during the process, the batter is transformed into a solid porous structure. Therefore, mass and heat transfer phenomena occur simultaneously, along with several biochemical reactions and physical transformations. In particular, depending on the product's formulation, volume expansion is not negligible; what is more, in some cases the product's volume may double its initial value by the end of the process.

Regarding the experimental characterization of cake baking, few researchers have focused simultaneously on both phenomena: volume expansion and heat transfer. Lostie et al. (2002) presented experimental temperature profiles of sponge cakes, baking the samples in a 1D isolated mould. The authors identified two baking periods, namely the 'heating up' and 'crust and crumb', and recorded the volume increase through a video camera, finding an important expansion followed by a slight shrinking at the end. Lara et al. (2011) followed expansion during baking of corn biscuits using a computer vision system and evaluated additional quality parameters (weight loss and colour). Concerning volume expansion, the authors found that it began when the internal temperature ranged from 45 to 50 °C, followed a sigmoid curve and ended when the surface crust appeared; higher oven temperatures induced higher volume expansion. Recently, Sani et al. (2014) experimentally studied the influence of baking conditions (oven temperature, natural or forced airflow condition, baking time) on volume development, texture parameters and moisture content of a standard butter cake, using a mould of regular dimensions. The authors informed a significant correlation between the baking conditions and the quality variables.

Besides, modelling enables a mathematical definition of the baking process, quantifying the interactions between the product and the oven environment, as well as the changes in the baked product (Sakin et al. 2007). From a mathematical point of view, bread is certainly the most studied baked product (Thorvaldsson and Janestad 1999; Wagner et al. 2007; Purlis & Salvadori 2010; Bikard et al. 2012; Ploteau et al. 2012, Flick et al. 2015). On the contrary, fewer studies focus on modelling of baking of sweet bakery products. Among others, Lostie et al. (2004) presented an attempt to model the crust-crumb formation during sponge cake baking, in order to evaluate physical parameters of both regions. This model satisfactorily predicted the crust thermal conductivity but it was inadequate in relation to crumb bulk viscosity, probably due to an oversimplified representation of the rheological behaviour of the crumb. Sakin et al. (2007) and Sakin-Yilmazer et al. (2012) solved the heat and mass transfer balances during baking of cupcakes and ring cake using an implicit finite differences scheme; the model was validated against their own experimental results. Ferrari et al. (2012) and Andresen (2013) simulated the biscuit baking process using a fixed 2D geometry and finite elements. Both models provide accurate predictions of the thermal profiles.

It is worth mentioning that none of these models incorporates the transfer mechanisms associated with volume expansion in products such as sponge cake, which do not only experiment a considerable expansion during baking, but also go through a structural transformation, changing from a fluid state to a porous solid state.

In consequence, the aim of this work is, in the first place, to study experimentally the influence of operative conditions (natural and forced convection; oven temperature, from 140 to 180 °C; steam addition) on the heat transfer dynamics and volume expansion during baking of sponge cake. Secondly, and following the experimental results, to develop a mathematical model to study the influence of operative conditions (air velocity, oven temperature, steam addition) on the heat transfer dynamics during baking, incorporating volume expansion. The model was solved by means of finite elements, using a deformable grid. Experimental volume increase was introduced into the mathematical model. Heat transfer was represented by Fourier's law, using physical properties adapted from literature and surface evaporation was taken into account in the apparent specific heat. Finally, the numerical results were validated with the experimental ones; accurate predictions of temperature profiles and baking times were obtained.

Materials and Methods

Sponge Cake Batter

Batter cake recipe was formulated with 270 g of whole fresh eggs, which were mixed during 2 min at 240 rpm in a multifunction food processor (Rowenta Universo 700, France). Then, 360 g of a dry premix (Tegral Satin Cake Premix, Puratos, Argentine—ingredients: fortified wheat flour, sucrose, wheat starch, chemical leavening agents, salt, artificial flavours) were added and mixed for another 2 min. The final batter composition was (w. b.): 45.4 % carbohydrates, 9.7 % proteins, 7.2 % fat, 1.7 % ashes and 36.0 % water. After mixing, 500 g of batter were dosed into an aluminium mould (18 cm diameter, 7 cm height).

Sponge Cake Baking

Baking tests were carried out in two batch-type electric ovens: a domestic oven (Ariston FM87-FC, Italy), and a semi-industrial convection oven (Multiequip HCE-3/300, Argentine). The domestic oven, whose chamber dimensions are 0.40 m (width) × 0.34 m (height) × 0.39 m (depth), was used for natural convection (NC) baking tests (with upper and lower resistances on). The convection oven, whose chamber dimensions are 0.42 m (width) × 0.35 m (height) × 0.4 m (depth), has a fan installed on the back wall, which propels the air at a fixed, single velocity of 2.8 m/s (this value was measured with a multifunction measuring instrument, TESTO 435, TESTO, Germany). The oven also has a manually controlled connection pipe, to provide steam into the chamber. This equipment allowed us to perform the baking tests in two modes: forced convection (FC) and steam-assisted forced convection (SFC). In the last mode, each test consumed ca. 600 ml water in the form of steam. The steam quantity was defined according to preliminary trials and published studies (Le Bail et al., 2011; Sakin-Yilmazer et al. 2013); it was injected in five equally spaced periods along the SFC baking tests. For all these three different baking modes, three series of experimental runs were performed, setting the nominal oven temperature at 140, 160 and 180 °C, respectively (nine total baking conditions). For all the tests, the oven was preheated during several minutes until it reached the pre-set temperature for each condition.

Volume Expansion

In order to measure volume change, a mould (same dimensions as described before) was adapted, fixing vertical bars to its bottom, placed in different positions along its diameter: $r = 0$ (centre, r0), $r = 0.035$ m (r3.5), $r = 0.065$ m (r6.5) and $r = 0.09$ m (mould wall, r9, Fig. 1). The bars have a marked

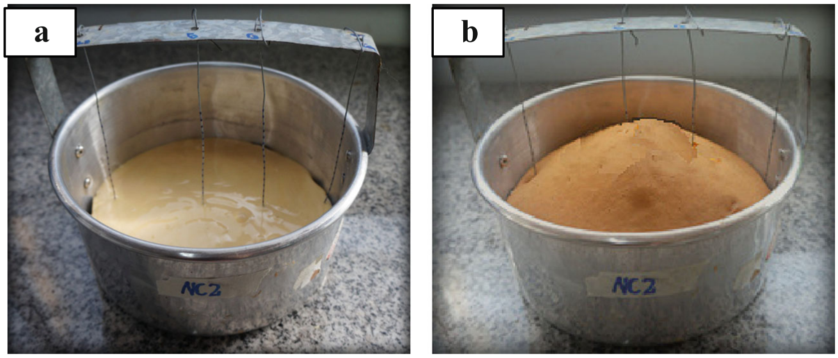

Fig. 1 Mould with fixed bars to measure volume expansion, **a** initial batter and **b** completely baked sponge cake

scale graduation of 5 mm printed on them to follow volume expansion.

These baking tests were carefully monitored by visual observation and with the help of a chronometer. The time at which the cake surface reached each mark was registered. This test was made by duplicate for each baking condition.

Temperature Measurement

Sponge cake temperature profile and oven temperature were recorded during the baking tests, using T-type thermocouples (Omega, USA) connected to a data logger (Keithley DASTC, USA). For the cake's temperature profile, three thermocouples were inserted inside the batter (without interfering with cake evolution), attached to the mould before filling it with the batter. The placement of the three thermocouples was chosen according to the results of preliminary trials, in which it was remarked that the initial geometrical centre of the batter does not represent the lowest temperature point when the baking process evolves. Thus, two of them were positioned in the axial axis of the sample ($r=0$) at 0.075 m (T1) and 0.055 m (T2) from the bottom mould. At the beginning of the baking process, both of them were outside the sample and they were covered while expansion occurred. The third one (T3) was positioned near the mould wall ($r=0.075$ m), 0.02 m from the mould bottom. This thermocouple was inside the sample during the whole experiment.

Oven temperature was recorded by placing two thermocouples in the centre of the oven chamber, near the sample. Two replicates were performed for each baking condition.

Mathematical Model

A mathematical model was developed. It focuses on simulating energy transfer during baking, and its solution provides the temperature profile inside the product and the baking time as a derived variable. For this kind of baked products, it is well known that mass transfer is only noticeable near the sample surface, where a dried crust is formed; the inner part of the sample (crumb) maintains the initial water content of the batter, being the average relation crust/crumb around 0.06 g g^{-1} (Ureta 2015). The proposed model takes into account the superficial water evaporation through the thermal properties, so that temperature profiles and baking times are influenced by product dehydration. Nevertheless, the model is unable to predict either water content or crust thickness.

Governing Equations and Boundary Conditions

The domain (Ω) is considered a continuous and homogeneous geometry that expands during baking. Simplified energy balance in the domain can be expressed as follows:

$$\rho C_{\mathrm{p}} \frac{\partial T}{\partial t} = \nabla(k \nabla T), \forall \Omega \qquad (1)$$

Notice that it is assumed that heat is transferred by conduction according to Fourier's law.

The boundary condition on the product's surface (Π) considers convection heat transfer using a global heat transfer coefficient h_c which depends on oven temperature T_{oven} and air circulation rate inside the oven chamber:

$$\nabla(\mathrm{k}\nabla\mathrm{T}) = h_{\mathrm{c}}(T_{\mathrm{oven}} - T), \forall \Pi \qquad (2)$$

In Eqs. 1 and 2, ρ, Cp and k are the product density (kg m^{-3}), the specific heat (J $kg^{-1}°C^{-1}$) and the thermal conductivity (W $m^{-1}°C^{-1}$), respectively; T (°C) is the temperature inside the product, T_{oven} (°C) is the temperature inside the oven chamber, t (s) is the time and h_c (W $m^{-2}°C^{-1}$) is the global heat transfer coefficient.

Thermophysical Properties

It is commonly assumed that thermal properties in foods (density, specific heat and thermal conductivity) depend on composition and temperature. In the present work, these properties were considered temperature dependent using expressions previously validated for baking of similar sweet bakery products: cupcakes (Baik et al., 1999; Sakin et al., 2007), biscuits (Ferrari et al., 2012) and muffins (Sakin-Yilmazer et al. 2013).

Global density ρ was experimentally determined for the initial batter (ρ_0) and for the final product (ρ_f) as the relation between weight and whole volume sample. To incorporate cake density variation during baking, it was considered the behaviour described by Baik et al. (1999) who studied thermal properties variation of a similar product (cupcake) during baking. The authors found that the product's density decreased linearly with temperature until reaching a stabilization value, which coincides with temperature stabilization inside the sample (100 °C). Given the experimental measured values, global density ρ (kg m^{-3}) was estimated as a function of inner temperature T:

$$\rho = \begin{cases} 1013 - 6.13T & T < 100 \\ 400 & T \geq 100 \end{cases} \quad (3)$$

With respect to specific heat C_p, the Bonacina et al. (1973) approach was adopted. Both contributions, latent heat and sensible heat, were summed:

$$C_p = C_{p\_sen} + C_{p\_lat} \quad (4)$$

$$C_{p\_sen} = \sum_i x_i C_{pi} \quad (5)$$

$$C_{p\_lat} = \frac{\Delta H_{vap}\, m_{water}}{\Delta T} \quad (6)$$

Sensible heat is calculated using the Choi and Okos (1986) model, based on the initial dough composition, where x_i is the component i mass fraction; $C_{pwater} = 4180$; $C_{pCH} = 1547$; $C_{pprot} = 1711$; $C_{pfat} = 1928$; $C_{pash} = 908$ (fibres and minerals); constant values expressed in J kg^{-1}°C^{-1}.

In Eq. 6, ΔH_{vap} is water vaporization enthalpy (2,257, 000 J kg^{-1}), m_{water} is the amount of water evaporated during baking (kg) and ΔT is the temperature interval assumed for the phase change (5 °C). This way, superficial water evaporation is incorporated through the apparent specific heat (Eq. 4).

Thermal conductivity k (W m^{-1} °C^{-1}) was evaluated taking into account an expression published for bread and similar products (Rask 1989), which considers that at temperature lower than 100 °C conductivity rises gradually, and then at 100 °C its value decreases significantly: water evaporates and is replaced by air. In that way, conductivity is expressed as:

$$k = \begin{cases} k_0 + 0.18\,10^{-2} & T \\ 0.2 \end{cases} \quad (7)$$

k_0 was determined considering the initial water content of the product, i.e. 0.27 W m^{-1}°C^{-1}.

To avoid the discontinuity produced by phase change (assumed at $T = 100$ °C) in the previous expressions, all of them were smoothed using Heaviside functions with OriginPro 8 software (Ferrari et al. 2012).

Global transfer coefficient, h_c, was measured during baking experiences with a heat flux sensor (Omega HFS4, USA). Given the small thickness and the high thermal conductivity of the mould, its transfer resistance was neglected and the same value of h_c was considered for the entire sample surface.

Numerical Simulation

Conforming to Eqs. 1 to 7, the energy transfer problem is defined by partial differential equations. Computational simulation offers the possibility to combine different aspects of a problem in a single solution, considering the dynamics and changes in the product properties as the process evolves. In this work, the finite element method (FEM) approach was applied using COMSOL Multiphysics 3.4 coupled with MATLAB 7.8.0, in order to introduce the thermal properties smoothed by Heaviside functions. A combination of 'Heat Transfer by conduction' module (Chemical Engineering Module/Energy transport/Conduction/Transient analysis) with 'Mesh displacement' module (COMSOL Multiphysics Module/Deformed Mesh/Moving mesh (ALE)/Transient analysis) allowed us to achieve a solution, both considering heat transfer and domain expansion.

The domain (Fig. 2) was defined by the half cross-sectional area of the cake considering axisymmetric 2D geometry (axes r and z) so that uniform energy transfer through lateral sides to the centre of the product was assumed (Zhang & Datta 2006; Andresen 2013). A mesh of triangular elements was applied, using the predefined *normal* element size. For this domain, heat transfer boundary conditions were axial symmetry on boundary 1 and convective heat transfer (h_c and T_{oven}) on boundaries 2, 3 and 4. Besides, mesh deformation was achieved assigning a prescribed displacement velocity v_z to the domain top surface (boundary 4), being this

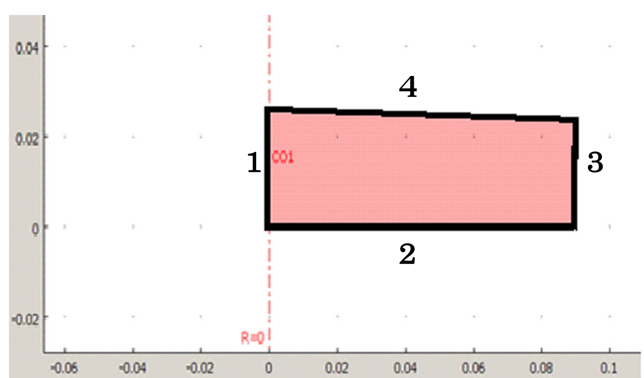

Fig. 2 The domain of simulation as it is represented in the graphics window of COMSOL Desktop. The boundaries of this domain are: *1* axial symmetry, *2* mould bottom, *3* mould wall and *4* cake surface

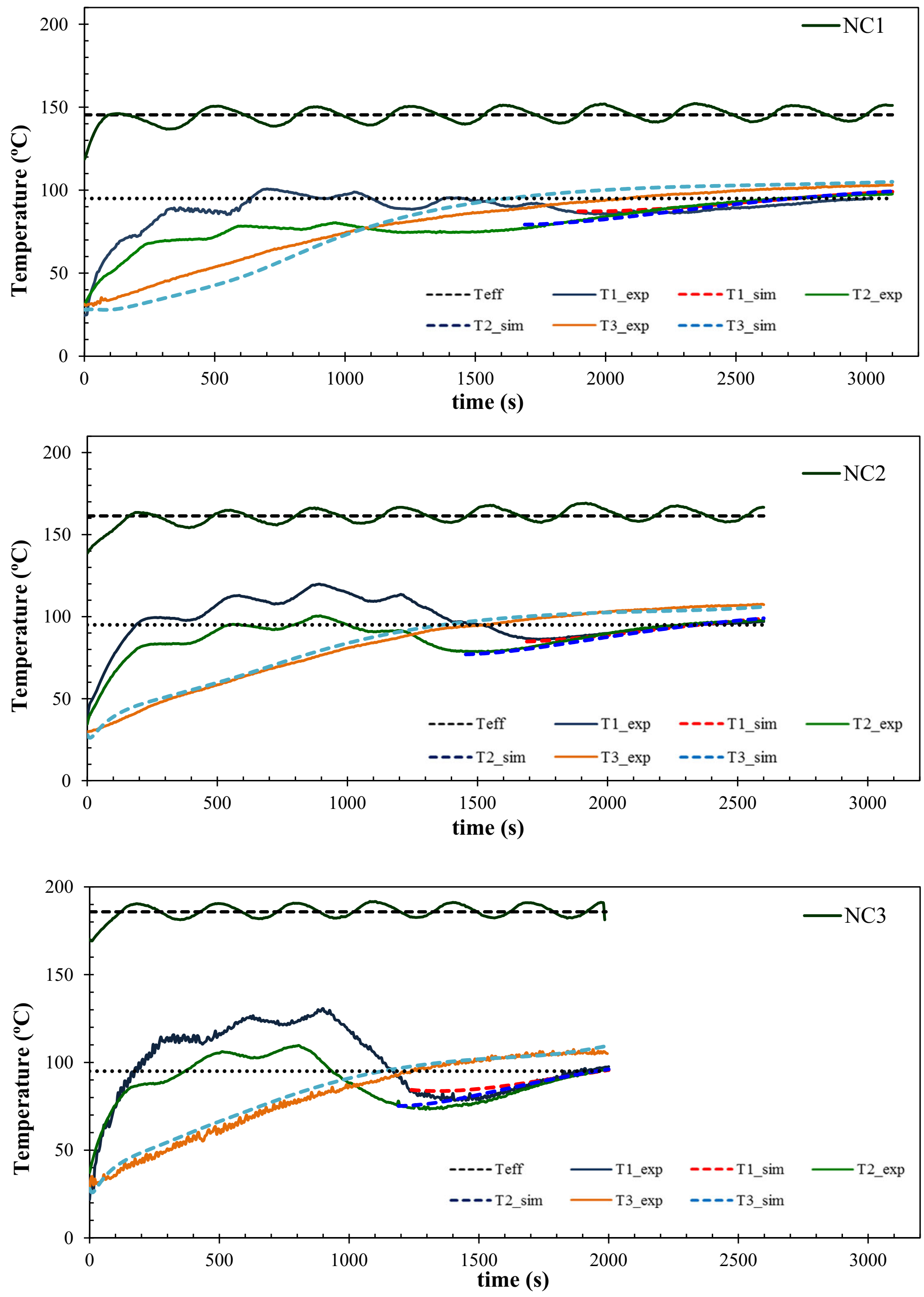

Fig. 3 Oven and sponge cake temperature profiles (T1_exp, T2_exp and T3_exp: experimental values, *full lines*; T1_sim, T2_sim and T3_sim: simulated values, *dashed lines*), *NC* natural convection; effective oven temperature (T_{eff}) for each condition is detailed in Table 1

parameter derived from experimental height evolution data analysis.

The whole problem was solved using transient analysis in COMSOL Multiphysics. The software detects nonlinearity of partial differential equations and evaluates the variables that contribute to the residual Jacobian and constrain Jacobian matrix. If both the two matrices are complete and do not depend on the solution, linear solver was used, otherwise nonlinear solver was used (Ferrari et al. 2012).

Validation

To verify model predicted values, V_{pred}, these were compared with experimental data, V_{exp}, and the absolute relative error, ε %, between them was estimated.

$$\varepsilon = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\left|V_{exp}-V_{pred}\right|}{V_{exp}}\right)100 \qquad (8)$$

Results and Discussion

Oven Temperature Profiles

Both ovens used in this work have an ON-OFF control system; for this reason, oven temperature during baking presents a periodic behaviour (Figs. 3, 4 and 5, for NC, FC and SFC modes, respectively). It is noticeable that NC mode had a smaller amplitude and higher period than FC and SFC modes; on the other hand, steam injection difficult the temperature control (non-uniform wave). Because of this oscillation, each baking condition was characterized with an effective temperature (T_{eff}, Table 1, dashed lines in Figs. 3, 4 and 5), which is calculated as the average value recorded during each baking test. In all the cases, this T_{eff} differs from the nominal temperature selected on the control panel of each oven. Besides, it was observed that the semi-industrial oven always induced higher effective temperatures than the domestic one. Nevertheless, the effective values are comparable due to the low range of variation associated with each one. Hence, each

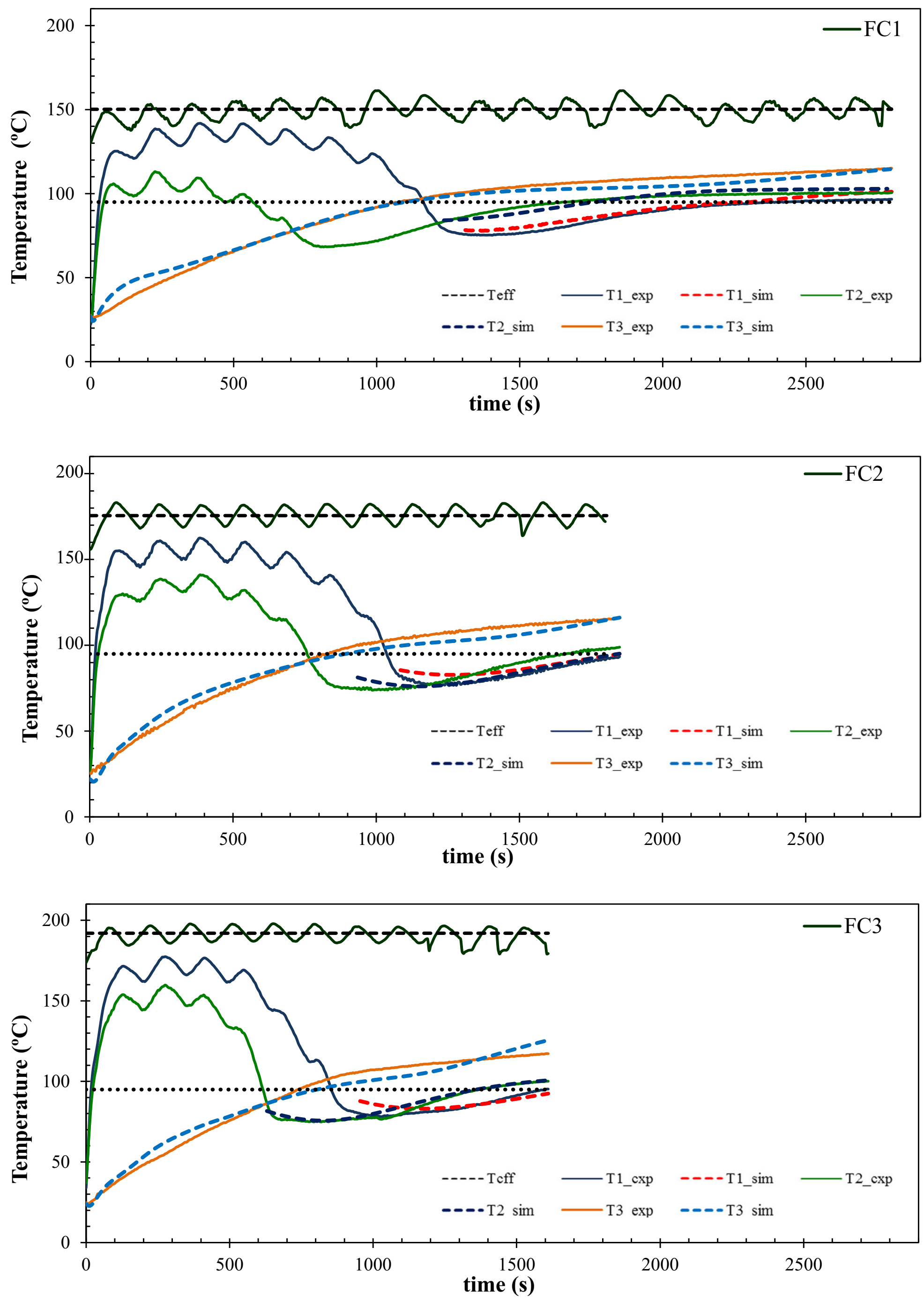

Fig. 4 Oven and sponge cake temperature profiles (T1_exp, T2_exp and T3_exp: experimental values, *full lines*; T1_sim, T2_sim and T3_sim: simulated values, *dashed lines*), *FC* forced convection; effective oven temperature (T_{eff}) for each condition is detailed in Table 1

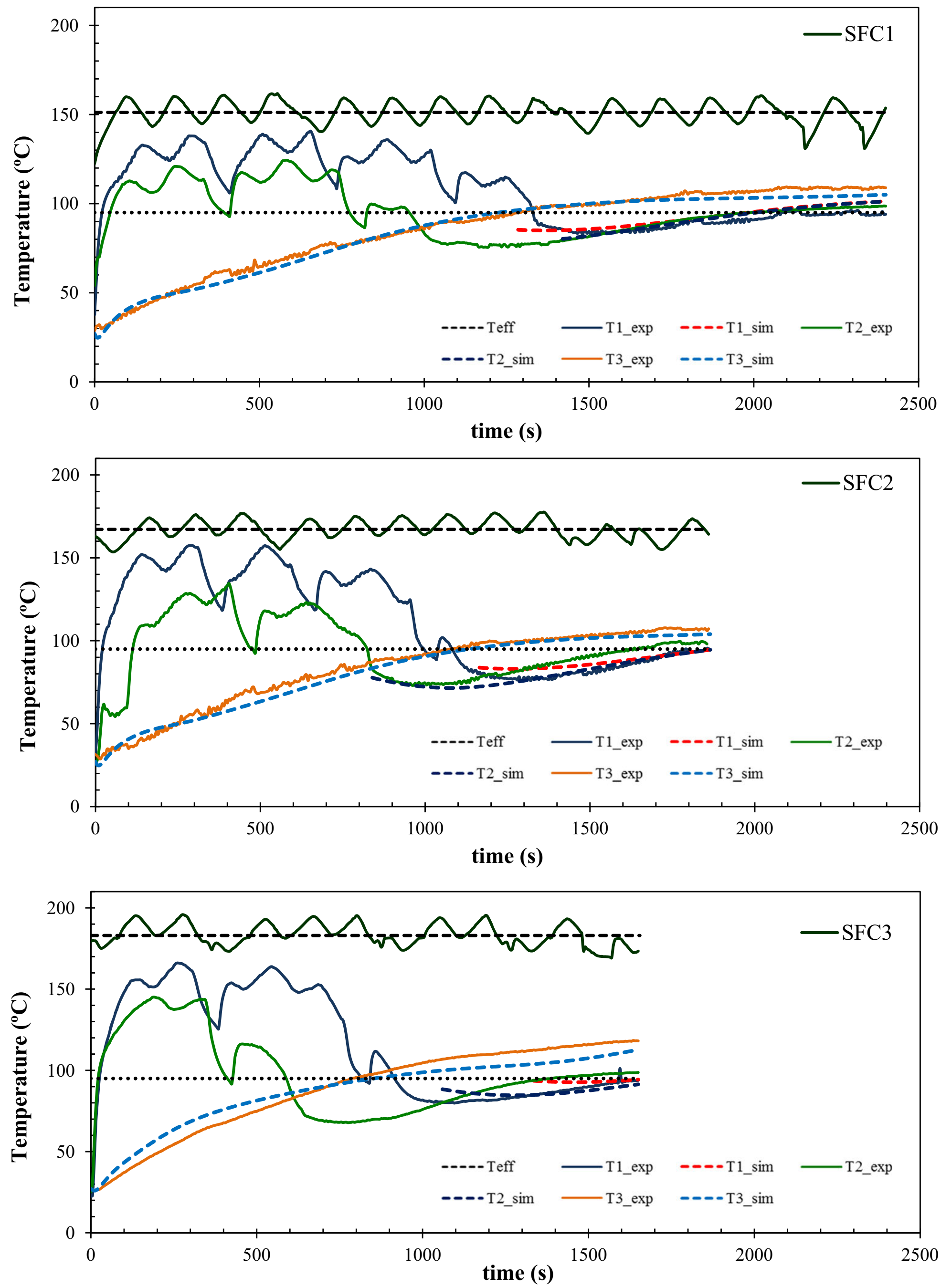

Fig. 5 Oven and sponge cake temperature profiles (T1_exp, T2_exp and T3_exp: experimental values, *full lines*; T1_sim, T2_sim and T3_sim: simulated values, *dashed lines*), *SFC* steam-assisted forced convection; effective oven temperature (T_{eff}) for each condition is detailed in Table 1

baking condition will be referred to according to the nomenclature presented in Table 1. Similar oven temperature fluctuations were reported by Ploteau et al. (2012) and Andresen (2013).

Volume Expansion

Figure 6 shows experimental (symbols) cake height evolution measured during baking under NC2 condition. Initially, it presents a lag phase (remains constant) and then it starts increasing gradually up to the final stabilization value. In addition, height evolution and its final value strongly depend on the sample's radial position. The same trend was observed for all the tested baking conditions. The final maximum experimental height at the centre of the sponge cake was between (0.086–0.091), (0.089–0.091) and (0.088–0.095) m for NC, FC and SFC modes, respectively. In each mode, an increase in oven temperature produced an increase in volume expansion. Additionally, an increase in airflow and steam injection favoured sponge cake volume expansion. This experimental behaviour was

Table 1 Nominal and effective oven temperature (°C) for the different operative conditions tested in this study

Nominal temperature	140	160	180
Natural convection	NC1	NC2	NC3
T_{eff}	145.4 ± 4.5	161.4 ± 4.7	185.8 ± 4.1
Forced convection	FC1	FC2	FC3
T_{eff}	150.2 ± 6.9	175.6 ± 4.9	194.0 ± 5.5
Steam-assisted forced convection	SFC1	SFC2	SFC3
T_{eff}	151.2 ± 6.3	166.2 ± 6.1	183.5 ± 6.7

previously reported by other researches in other sweet bakery products. Lara et al. (2011) monitored in real time the specific volume of corn biscuits. Baking experiments were performed under natural convection (190, 210, 230 and 250 °C); they found that biscuits baked at higher temperatures present higher volume expansion and that the expansion period ends when the surface dried crust appears. Sani et al. (2014) measured the volume expansion of butter cakes, using three oven temperatures (160, 170 and 180 °C) in natural and forced convection conditions. They found that volume expansion increases with temperature or air velocity; but oven temperature has a more significant effect than airflow condition.

In order to find a mathematical expression to incorporate volume expansion to the numerical model, the following fitting equation is proposed ($R^2 > 0.95$):

$$h = h_0 + (m - \mathrm{q}t - r^s)\left[1 - \left(1 + \frac{t}{n}\right)e^{-t/n}\right] \qquad 0 \le r \le R \qquad (9)$$

Eq. 9 allows the prediction of the sample height h (m) in relation to any radial position r (m), initial height h_0 (m) and time t (s); it represents correctly superficial shape evolution during cake baking (Ureta 2015). Also, calculated values of height evolution (lines) are presented in Fig. 6. The values of the empirical constants m, q, s and n (dimensionless) are detailed in Table 2 for the different processing conditions.

Finally, the displacement velocity v_z (m s^{-1}) to consider mesh deformation in the numerical model was calculated as the first derivative of height with respect to time:

$$v_z = (m - \mathrm{q}t - r^s)\left(\frac{t}{n^2}e^{-t/n}\right) \qquad (10)$$

Experimental Product Temperature Profile

During experimental work, it was observed that the last region to achieve a complete crumb development and an adequate degree of baking was the one near the axial axis (r0) just below the superficial top crust (Fig. 7). Notice that, even when the crust had reached a good level of dehydration and brown colour, the crumb just below might not have reached its appropriate structure characteristics (Fig. 7b). Therefore, it is critical to follow the temperature evolution of this region, which defined the strategic placement of thermocouples T1 and T2.

Many authors state that when bakery product inner temperature reaches 95–98 °C complete starch gelatinization and protein denaturation are achieved, thus the liquid emulsion is completely transformed in a solid porous structure (Ahrné et al. 2007; Purlis 2011; Paton et al. 2013). Furthermore, our research group confirms this fact in a previous work studying the baking process of muffin, a similar product to sponge cake under study (Ureta et al. 2014).

It is worth mentioning that, although the trials were made by duplicate, it was hard to reproduce the exact thermocouple positions due to the difficulties inherent to the experimental methodology. For this reason, Figs. 3, 4 and 5 show a single result for the temperature profiles (T1, T2 and T3) measured for each baking condition. In the early stages of baking, T1 and T2 present a periodic profile with values over 100 °C, which is not surprising as these two thermocouples initially were outside the batter and they recorded air oven temperature near the cake surface. Although this behaviour corresponds to air oven performance, the temperature recorded by these

Fig. 6 Experimental and calculated cake height vs. time, for different radial positions, natural convection, effective oven temperature 161.4 °C (NC2 condition)

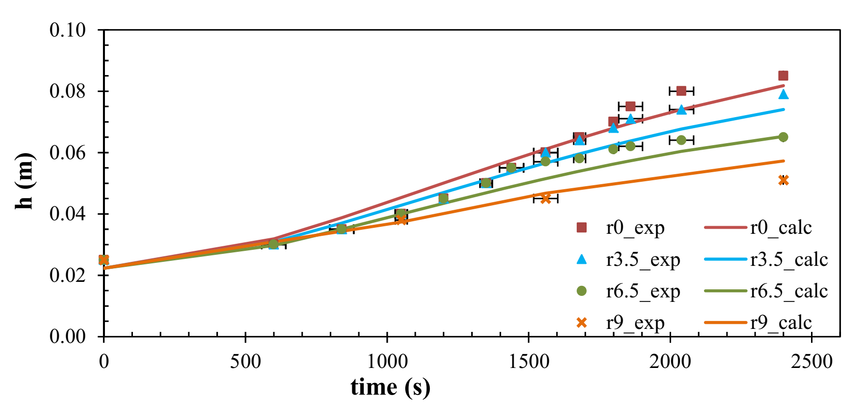

Table 2 Empirical constants (dimensionless) defined in Eqs. 9 and 10

	NC1	NC2	NC3	FC1	FC2	FC3	SFC1	SFC2	SFC3
m	0.105	0.170	0.113	0.173	0.180	0.180	0.162	0.140	0.162
q	$2.74\ 10^{-5}$	$1.77\ 10^{-5}$	$-8.71\ 10^{-6}$	$3.35\ 10^{-5}$	$2.75\ 10^{-5}$	$4.31\ 10^{-5}$	$2.43\ 10^{-5}$	$2.04\ 10^{-5}$	$3.01\ 10^{-5}$
s	1.304	1.222	1.188	1.124	1.100	1.250	1.150	1.106	1.053
n	1450	1524	1060	1000	1000	805	1160	903	719

thermocouples is considerably lower because they are close to the superficial region where dehydration occurs. What is more, T2, which is earlier inside the sample, shows lower temperature values than T1. As sponge cake expansion progresses, temperature measured by T1 and/or T2 starts to decrease gradually until it reaches a minimum value around 70–80 °C, instant at which the sample covers the thermocouple (from experimental observations). From that moment on, temperature increases up to stabilization value around 95 °C (indicated with a dotted line in Figs. 3, 4 and 5). On the contrary, T3 shows an increasing temperature during all the process; as its value is near 95 °C, its increasing rate slows down and finally stabilizes near 105 °C, before T1 and T2, given that T3 is close to the mould wall. This fact reinforces the idea that the last region to reach a correct degree of baking is the one near the crust around the axial axis (r0).

The general trends described for temperature profile (T1, T2 and T3) were observed in all the baking conditions studied.

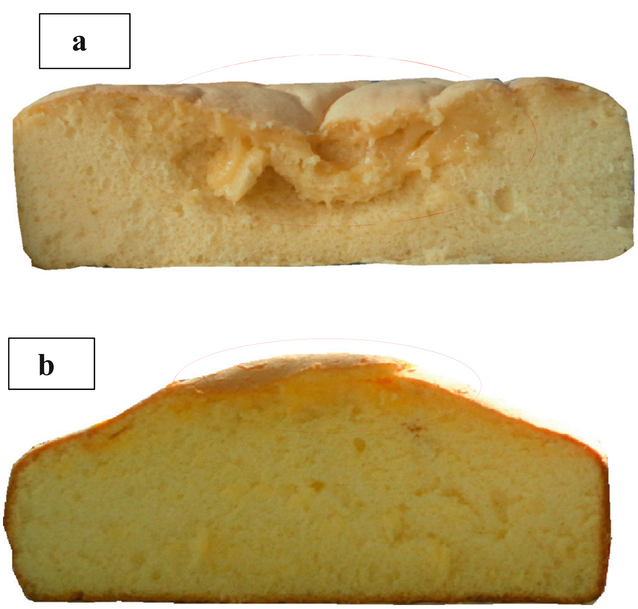

Fig. 7 Cake crumb at different process stages, natural convection, effective oven temperature 185.8 °C (NC3 condition). **a** Mid baking time and **b** close to minimal baking time

It is important to remark that considering this product volume, heat transfer defines the end of baking, other quality characteristics of a complete baked product as superficial colour or crust formation develop earlier than the complete crumb formation (Ureta 2015). A joint analysis of temperature profiles and experimental observations (Fig. 7) allowed us to define a minimal baking time ($t_{\min}$) as the average time at which T1 reaches the interval 95–98 °C.

In order to evaluate the effect of operative conditions on the minimal baking time, Fig. 8 presents the experimental values of this variable (full symbols) vs. the effective temperature for all baking conditions tested in this work. An exponential dependence (black lines) was found between baking time and effective temperature; clearly two data groups are differentiated: natural convection (NC, $R^2 > 0.99$) and on the other hand, forced convection (FC and SFC, $R^2 > 0.91$). Notice that according to the results from Table 1 and Fig. 8, steam injection influences the baking time through a decrease of effective temperature value as a consequence of the energy required to water evaporation.

Numerical Results

As it was mentioned, the heat transfer problem was solved using finite elements, simulating the different baking conditions tested in the experimental trials. In the boundary conditions 2 and 3 (bottom and wall of the mould, Fig. 2), T_{oven} was assumed equal to T_{eff} (Table 1). Instead, for boundary condition 4 (superficial top layer), the average value of experimental T1 and T2 (initial baking period) was adopted.

Global heat transfer coefficients (h_c) measured under these process conditions are 15, 25 and 20 (W m^{-2}°C^{-1}) for NC, FC and SFC baking modes, respectively. These coefficients are in the range of values informed by other researchers during cake baking in similar ovens (Lostie et al. 2004; Fehaili et al. 2010; Sakin-Yilmazer et al. 2012).

Thus, the model described by Eqs. 1 and 2, considering variable thermophysical properties (Eqs. 3 to 7) and all the boundary conditions aspects detailed before, is solved to simulate energy transfer during the cake baking process.

Firstly, Fig. 9 presents the domain expansion during simulation (SFC1 condition) from the beginning to the end of

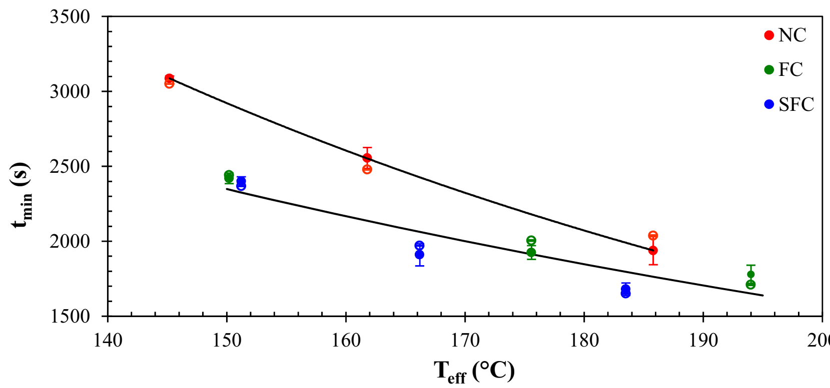

Fig. 8 Minimal baking times vs. T_{eff}. Experimental (*full symbols*) and predicted (*empty symbols*). *NC* natural convection, *FC* forced convection, *SFC* steam-assisted forced convection

baking. Similar volume increase was obtained for the rest of the studied conditions. As it can be seen, the model adequately represents cake expansion (height and shape).

Additionally, Figs. 3, 4 and 5 show the simulated temperature (dashed lines) of nodes (0, 0.075), (0, 0.055) and (0.075, 0.023) m which correspond to T1, T2 and T3 positions. In general terms, the model represents accurately the temperature profile inside the product. To corroborate this observation, model precision was evaluated according to the absolute relative error, ε (%, Eq. 8). This parameter provides values in a range of (1.6–5.5 %), (1.5–5.7 %) and (2.7–7.1 %) for T1, T2 y T3, respectively, for all baking conditions.

Considering these encourage error values, minimal baking times (t_{min}) were estimated from T1 predicted profiles (Fig. 8, empty symbols). As can be seen, two groups were identified: natural convection (NC) and forced convection (FC and SFC). Clearly, due to the energy required to vaporize the water, the steam injection affects the oven's effective temperature, and an increase in the minimal baking time is observed. Also, as it was expected, baking times were higher under natural convection conditions. Relative error, ε (%) with respect to experimental minimal baking time (Fig. 8, full symbols) was calculated. For all baking conditions tested, predicted t_{min} has an error less than 4 %.

Consequently, the developed mathematical model is a useful tool to calculate this process variable for sponge cake and similar sweet bakery products. In this manner, different process alternatives can be compared by avoiding experimental work.

Conclusions

In this work, sponge cake baking was studied considering three convection modes (NC, FC and SFC) and three different oven temperatures (140, 160 and 180 °C). A mathematical model was implemented to study the process heat transfer dynamics coupled with volume expansion.

As it was observed from height evolution results, volume expansion is significant and strongly depends on the radial position and the baking time. Besides, an increase in oven temperature, airflow and steam injection produces an increase in volume expansion. An empirical fitting equation was proposed to take into account this volume increase in the mathematical model. Simulated results adequately represent the observed evolution, that is, height and shape, of the sponge cake during its baking.

Concerning product temperature, both experimental and simulated profiles verified that the last region to achieve a correct degree of baking is the one near the crust around the axial axis. In consequence, the minimal baking time was defined as the average time at which this region reaches 95–98 °C. Finally, this process variable was strongly affected by the effective oven temperature, with a slight influence of the convection mode, that is, natural vs. forced ones.

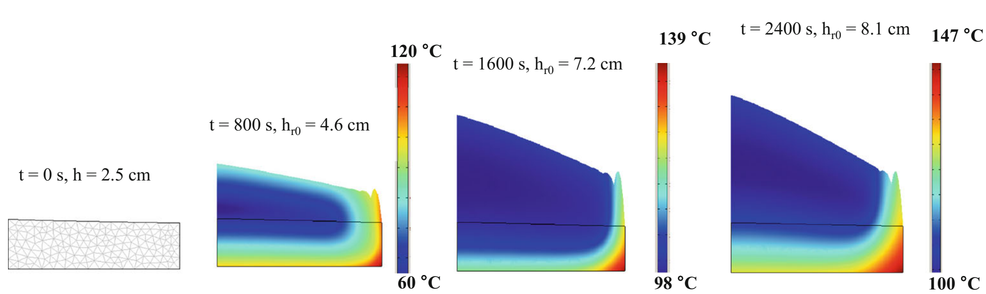

Fig. 9 Volume expansion simulated at different stages of baking, steam-assisted forced convection, effective oven temperature 151.2 °C (SFC1 condition)

Acknowledgments The authors acknowledge the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET, PIP GI 0180 and PIP IU 0259), Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT PICT 2013–1637) and Universidad Nacional de La Plata (UNLP, I183) from Argentina for their financial support.

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