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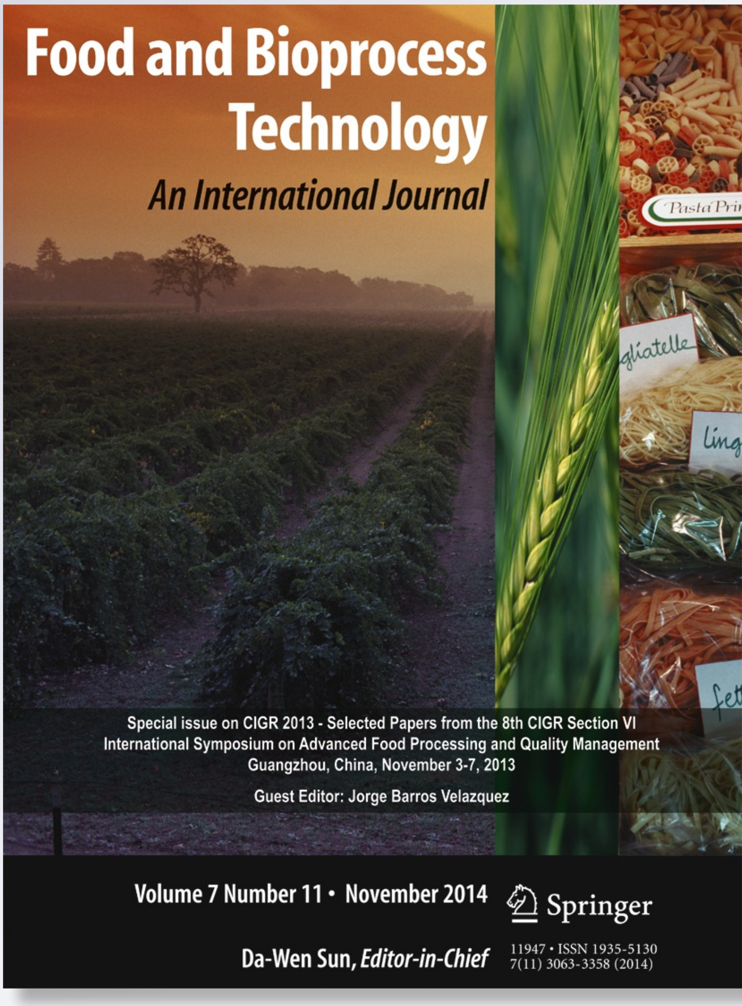

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ORIGINAL PAPER

Baking of muffins: Kinetics of crust color development and optimal baking time

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Abstract Baking is a decisive stage in the production of bakery products, in general—muffins, in particular—for most of the quality attributes of the final products depend on it. The aim of this work is to model the kinetics of muffin crust color development during baking and to evaluate the feasibility of this kinetic model to predict the baking times. Surface color is represented by the Browning Index, and the effect of baking temperature (from 140 to 220 °C) and process convective characteristics (natural convection, forced convection, and steam-assisted forced convection) are analyzed. Minimal baking times are calculated from experimental core temperature measurements. The modeling of browning kinetics, which incorporates the optimal crust color determined by sensory analysis, allows the estimation of optimal baking times. For all the tested conditions $t_{op} > t_{min}$, assuring a product whose inner structure was already totally baked. Finally, minimal, half, and optimal baking times present an exponential dependence with the oven temperature. Besides, there are no significant differences between both forced convection modes.

Keywords Browning Index · Crust color kinetics · Sensory analysis · Baking time

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Introduction

Baking is a decisive stage in the production of bakery products for most of the quality attributes of the final products depend on it (Schirmer et al. 2011). It is a complex process that combines heat and mass transfer between the environment and the product, in which both are responsible of transforming the mixture or initial dough into the final product (Purlis and Salvadori 2009a).

Optimizing this process is not a simple task, it depends on the product, its formulation, and the type of oven used (Xue et al. 2003; Purlis 2012). From the consumer point of view, optimizing the process means to find a condition that gives the product more acceptability and/or buying intention. Different quality attributes, such as texture, crumb water content, crust thickness and water content, aroma, and flavor, among others, contribute to the global quality of a bakery product. However, it is known that surface color is one of the first things the consumer perceives; it becomes a decisive factor to determine muffin acceptability and directly influences buying intention. Apart from being an attribute associated with the appearance and buying intention, surface color is a practical indicator of the progress of the baking process for this type of food; its evolution can be easily monitored during baking, hence being frequently used as indicator of end of process (Ahrné et al. 2007).

Its development is the consequence of caramelization and Maillard reactions during baking, favored by the high temperatures and the lower water content observed on the product crust.

Many authors have studied the surface color evolution of different bakery products during baking, bread being one of the most analyzed products. Among others, Zanoni et al. (1995) proposes a mathematical model for browning kinetics of bread crust during baking, expressed through a ΔE color difference defined as browning index. This model was also used by Chhanwal et al. (2011) who incorporated it to the modeling of bread baking with computational fluid dynamics (CFD). Purlis and Salvadori (2009b) reported a first-order kinetics for the evolution of color on the grounds of the variation of bread crust luminosity (L^*), associating the kinetics parameters with crust temperature and water content. Mundt and Wedzicha (2007) specifically worked on sweet bakery products and analyzed the effects of temperature and water activity on the browning kinetics during the baking of cookies. Sakin-Yilmazer et al. (2013) analyzed the effect of humidification in the browning reaction during the baking of muffins, and in a similar manner, Isleroglu et al. (2012) studied the baking of cookies.

Therefore, the aim of this work is to model the kinetics of muffin crust color development during baking and to evaluate the feasibility of this kinetic model to predict the baking times.

Surface color is represented by the Browning Index, a recognized useful variable to quantify the color change attributed to caramelization and Maillard reactions (Isleroglu et al. 2012; Ureta et al. 2014). The effect of two independent variables: baking temperature and process convective characteristics (natural convection, forced convection, and steam-assisted forced convection) are analyzed.

With respect to baking time prediction, core temperature records allow calculating minimal baking times, defined as time needed for the core to reach a 95–98 °C temperature, associated with a complete starch gelatinization, thus achieving a total transformation of the liquid emulsion in a solid porous structure. The modeling of browning kinetics, together with the product acceptability analysis based on a sensory study via a survival statistics, allows the estimation of optimal baking times.

Materials and Methods

Batter Preparation

The muffin batter was prepared from a ready to bake dry premix, Satin Cake Premix (Puratos, Argentina). The batter recipe was formulated with 250 g premix, 50 g fresh margarine, 100 ml fluid milk (reconstituted from 10 g powdered milk), and 60 g whole fresh eggs, which left a batter composition of 46.2 % carbohydrates, 5.3 % proteins, 14.0 % fat, and 34.5 % water. All ingredients were mixed for 5 min at a 240 rpm constant speed in a home multifunction food processor (Rowenta Universo 700, France). The final homogeneous mix was dosed (40 g) to fill individual disposable aluminum molds (47-mm diameter, 50-mm height).

Baking Tests

Baking experiments were carried out in two batch-type electric ovens: a domestic oven (Ariston FM87–FC, Italy), and a semi-industrial convective oven (Multiequip HCE-3/300, Argentina). 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 convective 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 propelled the air at a 2.8 m/s fixed single air velocity (this value was measured with a multifunction measuring instrument, TESTO 435, equipped with a vane probe, TESTO, Germany). The oven also has a connection pipe to provide steam to 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. 300 ml water to generate steam. For all these three different baking modes, five series of experimental runs were performed, setting the nominal oven temperature at 140, 160, 180, 200, and 220 °C, respectively (15 total baking conditions). For all the tests, each oven was preheated for several minutes until they reached the preset temperature. Three replicates were performed for each baking condition.

Temperature Measurement

Muffin core temperature (T) and effective oven temperature (T_{eff}) were recorded during the baking tests, using the T-type thermocouples (Omega, USA) connected to a data logger (Keithley DASTC, USA).

For measuring muffin temperature, thermocouples were inserted inside the batter, in a vertical position, fixed to the mold before filling and baking it. Three replicates of this measure were performed for each baking condition.

Oven temperature was recorded by placing two thermocouples in the middle of the oven chamber, near the samples.

Kinetics of Crust Color Development

To monitor the evolution of muffin surface color, partial baking experiments were performed. In this sense, the most relevant instances during the baking process (nine for each studied condition) such as initial batter, early formation of crust, several intermediate values, and a final crust representing the color of a completely burnt product were observed. At these selected baking times, the samples were removed from the oven, surface color was immediately measured, and finally the sample was discarded. For this purpose, a MINOLTA CR-300 tristimulus colorimeter (Osaka, Japan) was used, recording the CIE $L^*a^*b^*$ parameters. Reported values for each time and oven temperature condition correspond to a 15 measurement average.

According to literature (Buera et al. 1986, Isleroglu et al. 2012; Sakin-Yilmazer et al. 2013), the browning index (*BI*), as defined in Eq. (1), is an appropriate variable to relate *Lab*, the three color parameters.

$$BI = \frac{100(x - 0.31)}{0.172} \tag{1}$$

where:

$$x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)}$$

In an earlier work (Ureta et al. 2014), it was observed that *BI* evolution during baking presented a similar behavior, despite oven temperature, with the same initial batter value for all conditions, ca. 28, then a period of induction was verified, and finally, the *BI* augmented gradually until reaching, asymptotically, a final value close to 160, which represented a totally burnt product. Generally, this behavior could be represented by a sigmoid curve, as shown in Eq. (2):

$$BI = BI_0 + \frac{BI_{max} - BI_0}{1 + \exp(-k(t - t_{1/2}))} \tag{2}$$

where BI is the browning index measured at time t, BI_0 is the initial browning index (at t=0), k is the browning rate constant (s^{-1}), BI_{max} is the maximum browning index which represents the surface color of a burnt muffin, and $t_{1/2}$ is the time (s) when half of the maximum browning index is reached. As previously mentioned in this study, the product was the same for all baking tests, so BI_0 and BI_{max} were equal to 28 and 160, respectively. As a consequence, the proposed model had two parameters that, depending on baking condition, were k and $t_{1/2}$.

Optimal Surface Color

A consumer panel formed by fifty (50) usual muffin consumers from La Plata (Buenos Aires, Argentina) ranging from 25 to 65 years of age, half of them female and the other half male, evaluated muffin surface color. The purpose of this sensory study was to obtain an optimal surface color value, using survival statistics concepts, the key concept of this methodology being focusing the hazard on the consumer rejection of the product (Garitta et al. 2006).

Each panelist received five samples obtained at different baking times, therefore presenting different surface colors, which corresponded to five different *BIs*: 67, 81, 101, 116, and 126, respectively. These samples were obtained under conventional baking mode (NC) performed at 160 °C. Panelists, placed in a room at ambient temperature with uniform light, were asked to indicate their perception about surface color of samples randomly ordered. In the questionnaire given, they should only write whether the samples were "Too light," "Too dark," or "Ok," without tasting them.

We will briefly describe the methodology used: Let A be the random variable representing the optimum color value for a consumer. Assume that A is absolutely continuous with distribution function *F*. For each value of browning index *BI*, there will be two rejection functions:

$R_l(BI)$ = percent of consumers rejecting muffins with color = BI because they are too light,
i.e. : $R_l(BI) = P(A > BI) = 1 - F(BI)$
$R_d(BI)$ = percent of consumers rejecting muffins with color = BI because they are too dark,
i.e. : $R_d(BI) = P(A < BI) = F(BI)$

Data were fitted by maximizing the likelihood function for five standard distributions (Weibull; normal, lognormal, logistic, and loglogistic). The likelihood function is a mathematical expression that describes the joint probability for obtaining the data actually observed on the subjects of the study as a function of the unknown parameters of the distribution being considered (Lopez Osornio et al. 2008). All analyses were conducted using R 3.0.1 (2013).

Statistical Analysis

The experimental data was subjected to the analysis of variance. Comparison of means was conducted by using Fisher's least significant difference test, with a 5 % significance level.

Results and Discussion

Temperature Profile

First of all, temperature monitoring in the chamber during the baking process allowed verifying that the real temperature of the baking environment is not constant. The recorded variation was±5.9, ± 7.5, and±6.4 °C for natural convection, forced convection, and steam-assisted forced convection, respectively. The high air recirculation values in the semi-industrial oven would be responsible for the fluctuations in the temperatures observed. Hence, considering these observations, for the result analysis, the operative effective temperature (T_{eff}), defined as the average value of the temperature

Table 1 Nominal and effective oven temperatures for the different operative conditions tested in this study

Nominal temperature (Celsius)	Effective temperature (Celsius)					
	Natural convection		Forced convection		Steam-assisted forced convection	
140	NC1	134.7±5.0	FC1	154.0±5.1	SFC1	142.7±4.6
160	NC2	150.6±5.0	FC2	173.1±5.1	SFC2	151.6±7.0
180	NC3	179.5±10.2	FC3	194.0±5.5	SFC3	173.7±7.9
200	NC4	208.6±2.7	FC4	213.7±7.8	SFC4	191.5±7.8
220	NC5	230.2±9.3	FC5	235.0±6.2	SFC5	197.7±6.5

values recorded at each condition during the whole essay, was taken as representative of each baking condition. Table 1 presents the nomenclature used and the nominal and effective conditions for all tested conditions.

Once in the oven, a combination of heat and mass transfer phenomena between the product and the baking environment occurs. As a consequence of these transfers, inside the muffin, there is a temperature increase that favors physical and chemical reactions, which in turn are responsible of the porous structure formation and the development of the sensory characteristics, typical of bakery products (Hadiyanto et al. 2007; Vanin et al. 2009). Fig. 1 presents the product thermal history for all the tested conditions.

Both for the FC and SFC conditions, the curves show an initial lag phase (ca. 150 s for FC and 200 s for SFC), where temperature remains between 25 and 35 °C without major changes, then it is observed that inside temperature increases in a linear manner in time.

On the other hand, baking under NC produces a gradual heating at the beginning with slight changes, then there is an increase in the slope of the temperature vs. time curve, though heating is always lower than in both cases of forced convection.

Independently of these particulars characterizing each baking condition, a common behavior is noted in all tests. At a certain instance of the process, the inner temperature stabilizes at a value ca. 100 °C, graphically identified as a plateau in the temperature profile vs. time. A similar behavior was observed by different authors in different sweet baked products (Lostie et al. 2002; Fehaili et al. 2010; Sakin et al. 2007).

In this work, we will identify this typical time, from which inner temperature no longer increases, as minimal baking time, t_{min}, due to the fact that it has been experimentally observed that when reaching said process time, crumb already presents a completely developed solid porous structure.

In this sense, numerous authors have used the bakery product inner thermal histories to define a baking time that assures complete starch gelatinization and protein denaturation, features that are achieved when the product temperature reaches 95–98 °C (Therdthai et al. 2002; Ahrné et al. 2007; Purlis 2011; Paton et al. 2013).

According to the thermal history recorded (Fig. 1), this variable takes values in a range of 430–985, 240–475, and 350–545 s for the NC, FC, and SFC conditions, respectively.

With the purpose of analyzing the minimal baking time dependence with the baking operative conditions, Fig. 2a shows such variable, taking into account the effective temperature for the different tested conditions. Minimal baking time presents an exponential dependence with T_{eff} ($R^2>0.94$), where two data sets or groups can be identified: natural convection (NC) and forced convection (FC and SCF), respectively. According to these results, the steam injection effect is only manifested in a decrease in baking effective temperature, owing to the heat required to vaporize the liquid water supplied.

To conclude this analysis, it should be mentioned that minimal time cannot be considered a typical feature of complete baking of the product; in the case of muffins, when the required time is reached, it is observed that in none of the baking conditions tested has the product completely developed the sensory characteristics that strongly conditions its acceptability, mainly the dehydrated crust with its typical brownish golden color.

Kinetics of Crust Color Development

Color is a very important property, which defines the acceptability of baked products by the consumer; the extent of browning also determines the flavor of the finished product. Moreover, as color development occurs largely during the later stages of baking, it can be used to judge completion of the baking process (Mundt and Wedzicha 2007).

Particularly in the muffin baking process, it has been observed that at a first instance, the emulsion begins to increase its volume until becoming a solid with its own distribution of pores in the inside (as previously mentioned, this instance corresponds to baking minimal time). In turn, as a consequence of heat and mass transfers between the product and the environment, the product surface dehydrates and color development is observed as a result of Maillard reaction and sugar caramelization. As it is known, the extent of these chemical reactions is largely influenced by the physical

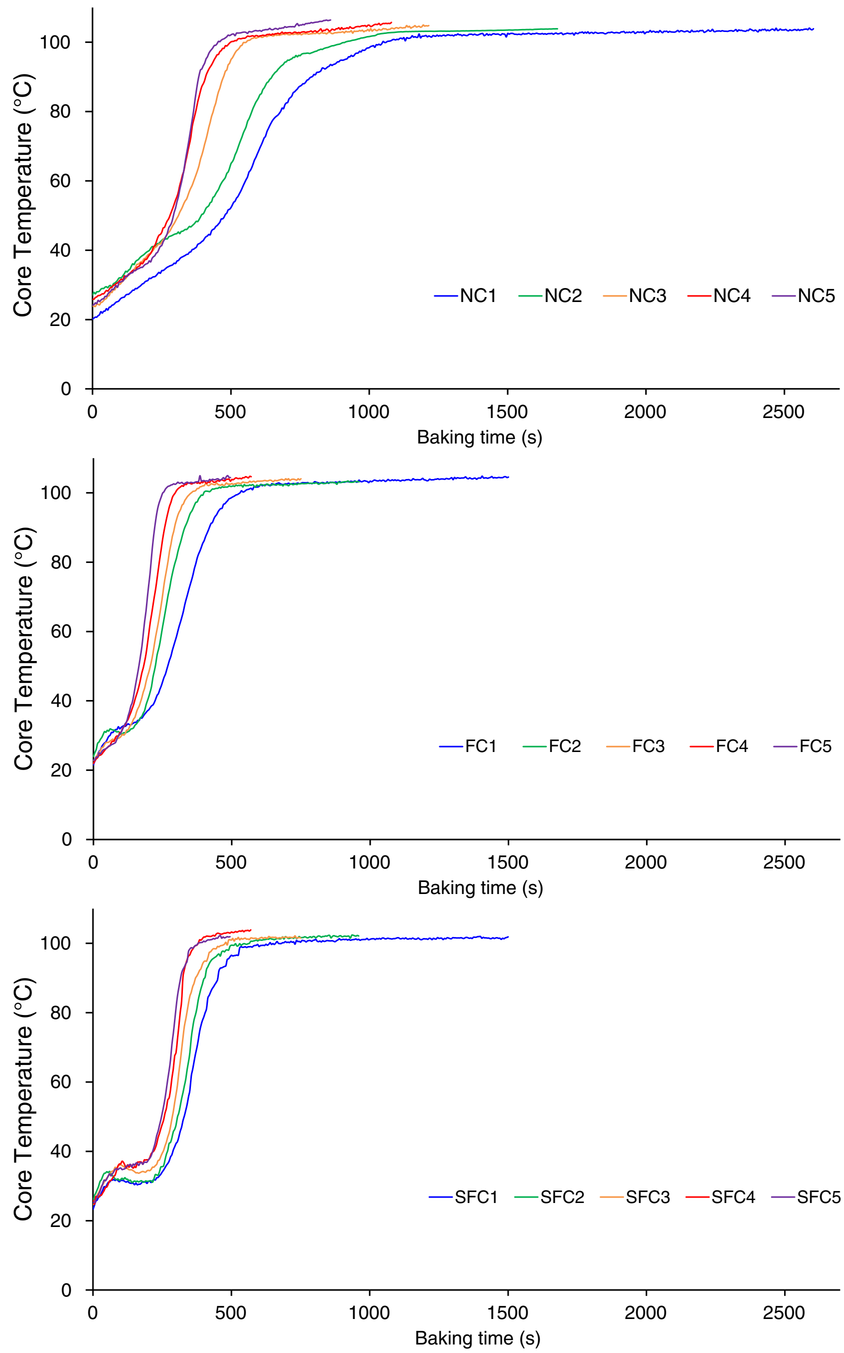

Fig. 1 Experimental baking curves obtained for the different operative conditions. *NC* natural convection, *FC* forced convection, *SFC*: steam-assisted forced convection. The oven temperature for each condition is detailed in Table 1

mechanisms of heat and water transfer during baking, which are strongly dependent on the processing conditions during baking, i.e., time, temperature, air velocity, air relative humidity, and rate of heat transfer.

The Maillard reaction is important for the formation of color and aroma in the crust, but may also be associated with the formation of toxic compounds such as acrylamide (Ahrné et al. 2007).

Hence, surface color followup during baking is important to identify the moment at which the product reaches the color defined as optimum by consumers.

In this paper, the followup was done using the *BI* parameter. Under all tested conditions, the same tendency has been observed: an initial period during which the *BI* presents no variation, followed by an increase, whose speed depends on the baking condition, and finally a plateau, where color is already too dark (burnt) and *BI* value stabilizes ca. 160 (Ureta et al. 2014). The experimental results and the adjustment proposed in Eq. (2) are presented in Fig. 3, demonstrating that the kinetic model proposed represents surface color evolution ($R^2 \geq 0.96$) with sufficient accuracy. Hence, it is necessary to analyze the dependence of the two parameters of this model (*k*

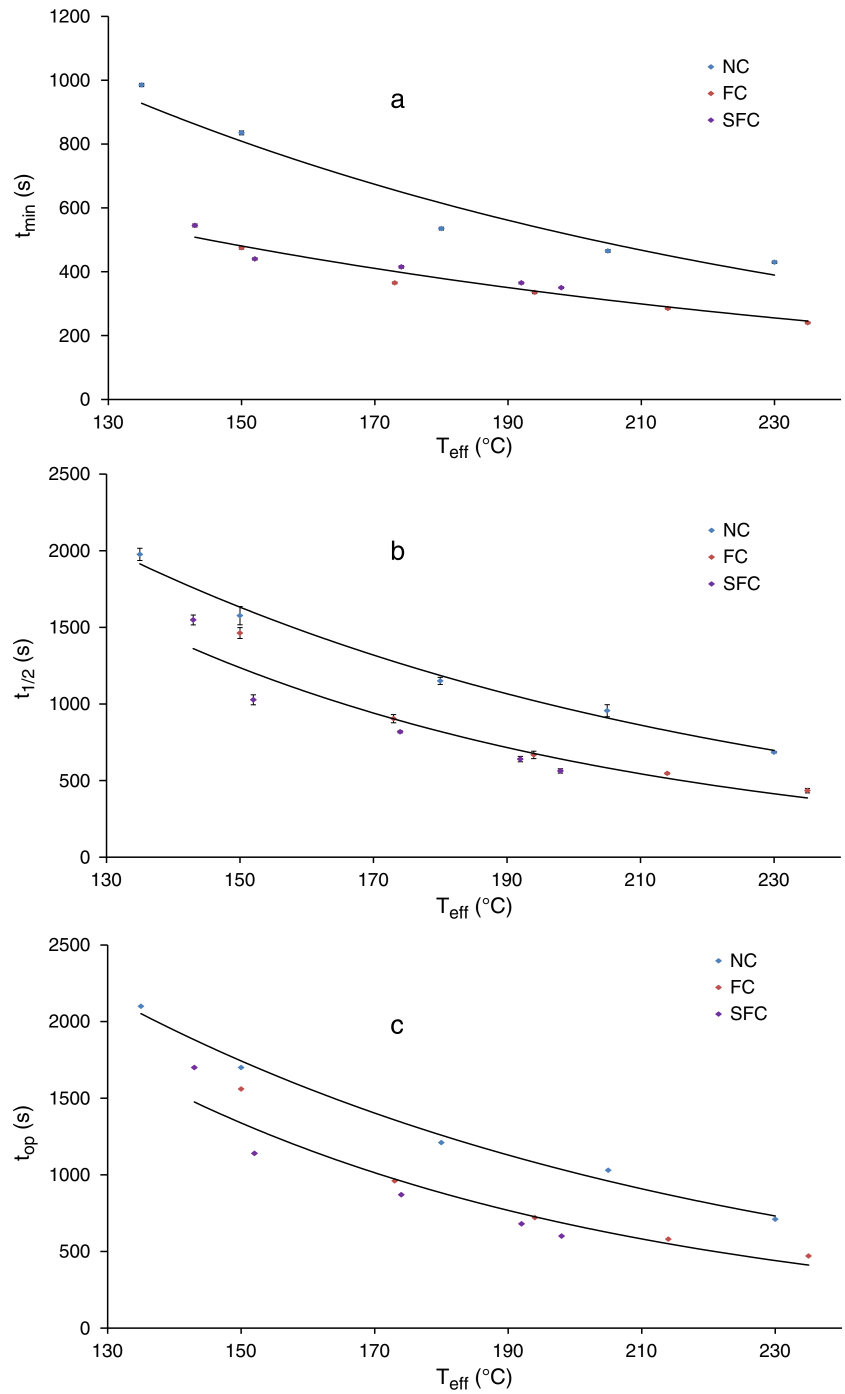

Fig. 2 Minimal (**a**), half (**b**), and optimal (**c**) baking times [*symbols*: experimental (**a**, **b**) or predicted (**c**); *lines*: exponential tendency] for the different operative conditions. *NC* natural convection, *FC* forced convection, *SFC* steam-assisted forced convection

and $t_{1/2}$) with the operative conditions, which, in our case, comes down to two variables, a continuous one, i.e., the effective baking temperature, and a discrete one, i.e., the mode in which the oven operates (NC, FC, and SFC).

These parameters are presented in Table 2. It is important to notice that both k and $t_{1/2}$ significantly depend on the baking effective temperature. Regarding the mode of operation influence, we again see that there are no significant differences between FC and SFC.

The dependence of kinetic constant k with effective temperature follows a behavior that adjusts to Arrhenius equation, defined by an activation heat E_a and a pre-exponential factor k_0. The E_a (kilojoule per mole) is equal to 23.08±7.49 and 27.09±4.08 for NC and FC/SFC conditions, respectively. The pre-exponential factor k_0 (per second) is equal to 2.51±0.69 and 8.41±0.08 for NC and FC/SFC conditions, respectively. The E_a values are within the range found by other authors regarding color evolution: Zanoni et al. (1995)) have analyzed

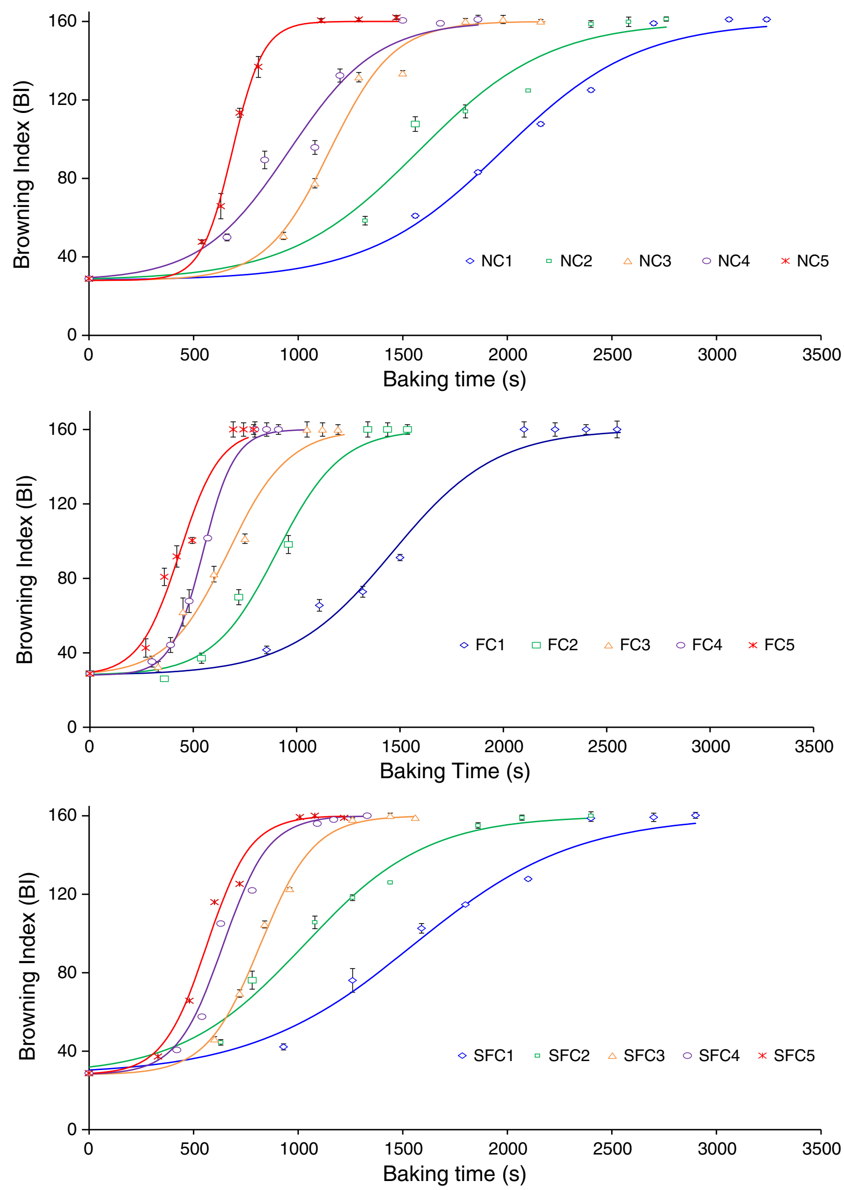

Fig. 3 Browning index [*symbols*: experimental, *lines*: Eq. (2)] for the different operative conditions. *NC* natural convection, *FC* forced convection, *SFC* steam-assisted forced convection. The oven temperature for each condition is detailed in Table 1

surface color evolution during bread baking following the ΔE parameter, a process characterized by an activation energy of 64.15 kJ/mol; Broyart et al. (1998)) analyzed lightness parameter L^* evolution in crackers finding an activation energy within the 70–90 kJ/mol range; Sakin-Yilmazer et al. (2013) found that surface color evolution in muffins, monitored through acrylamide concentration present an activation energy of 36.35 kJ/mol.

On the other hand, the kinetic parameter $t_{1/2}$, presenting values within the 1,980–685, 1,463–435, and 1,565–550

Table 2 Fitting parameters of the *BI* model, represented by Eq. (2)

Natural convection			Forced convection			Steam-assisted forced convection		
	$t_{1/2}$ (second)	k (per second)		$t_{1/2}$ (second)	k (per second)		$t_{1/2}$ (second)	k (per second)
NC1	1,976.12±39.79	3.09±0.03	FC1	1,462.67±35.67	4.00±0.03	SFC1	1,564.40±32.40	2.86±0.03
NC2	1,576.26±59.73	3.21±0.02	FC2	903.84±26.64	6.45±0.04	SFC2	1,014.06±32.60	3.35±0.03
NC3	1,150.68±23.16	6.49±0.04	FC3	667.71±24.03	6.84±0.04	SFC3	799.86±7.37	7.90±0.12
NC4	956.35±39.35	4.73±0.03	FC4	546.74±4.82	11.10±0.21	SFC4	561.37±17.44	9.68±0.05
NC5	685.13±5.07	13.46±0.20	FC5	434.59±14.68	10.23±0.06	SFC5	550.50±14.29	9.46±0.07

range for NC, FC, and SFC, respectively, decrease with the increase of T_{eff}, following an exponential dependence with effective temperature, (R^2>0.93, Fig. 2b). This behavior is similar to that observed for minimal baking times; therefore, there are no significant differences between FC and SFC conditions.

Optimal Surface Color

The application of the survival statistics concept to the results of the sensory test allowed finding the R_l and R_d rejection functions; hence, Weibull distribution, detailed in Eqs. (3a) and (3b), being the most appropriate to adjust them. The values of the parameters μ and σ are 4.541±0.040 and 0.124±0.029 for R_l and 4.806±0.012 and 0.034±0.009 for R_d, respectively.

$$R_l(BI) = 1 - \exp\left[-\exp\left(\frac{\ln(BI)-\mu}{\sigma}\right)\right] \quad (3a)$$

$$R_d(BI) = \exp\left[-\exp\left(\frac{\ln(BI)-\mu}{\sigma}\right)\right] \quad (3b)$$

Fig. 4 shows both rejection curves, it also shows the global curve resulting from R_l and R_d addition. Thus, the optimal value searched for corresponds to the minimum of the latter curve, resulting in a *BI* value equal to 108±2 associated with a 6.72 % rejection percent (only three consumers out of 50 surveyed rejected this product for being too light or too dark).

Optimal Baking Time

Based on the previous results, the proposed kinetic model allows us to estimate the needed baking time to achieve the optimal surface color, which will be defined as optimal baking time t_{op}. For this product, in particular, this time is always greater than t_{min}, thus assuring that the product is completely baked from the point of view of inner structure formation.

Adopting as optimal *BI* value the value determined by the sensory analysis (108), Eq. (2) allows estimating the optimal time since the kinetic model parameters are already determined (Table 2) for all baking conditions tested in this study. These results are shown in Fig. 2c in a similar manner to other typical times taking into account the oven effective temperature and the operative mode. The t_{op} calculated values vary within a 710–2,100, 470–1,560, and 600–1,700 range, respectively. As it is to be expected, as oven temperature increases optimal time decreases, again following an exponential function (R^2>0.94). Once again, both forced convection modes, FC and SFC, can be jointly analyzed since there are no significant differences between them.

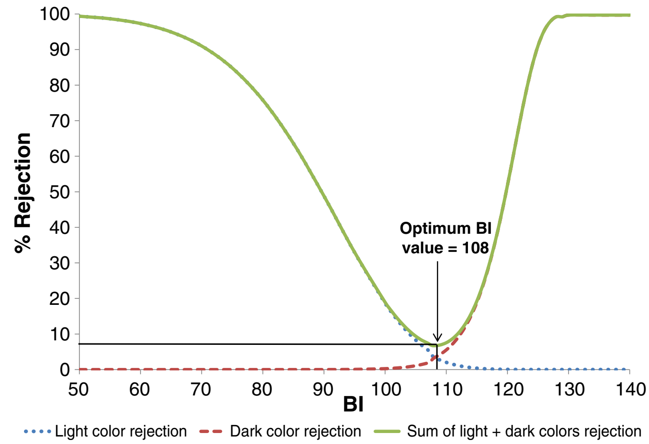

Fig. 4 Rejection curves obtained from sensory analysis for light and dark muffin surface color. Optimum value of browning index is also indicated

Conclusions

In this work, the influence of baking conditions (oven temperature and baking conditions: NC, FC ,and SFC) on the development of surface color was analyzed.

The proposed kinetic model allowed associating *BI* color development identification with operative conditions. For the air circulation speed conditions used in forced convection, it was found that water steam incorporation to the baking chamber did not affect the trends found; it only manifested in a significant effective temperature decrease, which caused longer baking time.

The sensory analysis through survival statistics allowed defining the crust optimal color value based on the preferences of the habitual consumers of this product.

Finally, these two aspects interrelation allowed defining optimal baking times, assuring a product whose inner structure was already totally baked (t_{op}>t_{min}) and with a high acceptance degree (minimal rejection).

To conclude, the trends found for baking times are a valid tool to define process times for this product, in particular; its extrapolation to other baked products should be thoroughly analyzed.

References

Ahrné, L., Andersson, C. G., Floberg, F., Rosén, J., & Lingnert, H. (2007). Effect of crust temperature and water content on acrylamide formation during baking of white bread: steam and falling temperature baking. *LWT - Food Science and Technology, 40*(10), 1708–1715.

Broyart, B., Trystram, G., & Duquenoy, A. (1998). Predicting color kinetics during cracker baking. *Journal of Food Engineering, 35*, 351–368.

Buera, M. P., Lozano, R. D., & Petriella, C. (1986). Definition of colour in the non enzymatic browning process. *Die Farbe, 32*(33), 318–322.

Chhanwal, N., Indrani, D., Raghavarao, K. S., & Anandharamakrishnan, C. (2011). Computational fluid dynamics modeling of bread baking process. *Food Research International, 44*, 978–983.

Fehaili, S., Courel, M., Rega, B., & Giampaoli, P. (2010). An instrumented oven for the monitoring of thermal reactions during the baking of sponge cake. *Journal of Food Engineering, 101*, 253–263.

Garitta, L., Serrat, C., Hough, G., & Curia, A. (2006). Determination of optimum concentrations of a food ingredient using survival analysis statistics. *Journal of Food Science, 71*(7), S526–S532.

Hadiyanto, H., Asselman, A., van Straten, G., Boom, R. M., Esveld, D. C., & van Boxtel, A. J. B. (2007). Quality prediction of bakery products in the initial phase of process design. *Innovative Food Science and Emerging Technologies, 8*, 285–298.

Isleroglu, H., Kemerli, T., Sakin-Yilmazer, M., Guven, G., Ozdestan, O., Uren, A., et al. (2012). Effect of steam assisted baking on acrylamide formation and browning kinetics of cookies. *Journal of Food Science, 77*, E257–E263.

Lopez Osornio, M., Hough, G., Salvador, A., Chambers, E., IV, McGrawc, S., & Fiszman, S. (2008). Beef's optimum internal cooking temperature as seen by consumers from diferent countries using survival analysis statistics. *Food Quality and Preference, 19*, 12–20.

Lostie, M., Peczalski, R., Andrieu, J., & Laurent, M. (2002). Study of sponge cake batter baking process: Part I. Experimental data. *Journal of Food Engineering, 51*, 131–137.

Mundt, S., & Wedzicha, B. (2007). A kinetic model for browning in the baking of biscuits: Effects of water activity and temperature. *Lebensmittel-Wissenschaft und-Technologie., 40*, 1078–1082.

Paton, J., Khatir, Z., Thompson, H., Kapur, N., & Toropov, V. (2013). Thermal energy management in the bread baking industry using a system modelling approach. *Applied Thermal Engineering, 53*, 340–347.

Purlis, E. (2011). Bread baking: Technological considerations based on process modeling and simulation. *Journal of Food Engineering, 103*, 92–102.

Purlis, E. (2012). Baking process design based on modelling and simulation: Towards optimization of bread baking. *Food Control, 27*, 45–52.

Purlis, E., & Salvadori, V. O. (2009a). Bread baking as a moving boundary problem. Part 1: Mathematical modelling. *Journal of Food Engineering, 91*, 428–433.

Purlis, E., & Salvadori, V. O. (2009b). Modelling the browning of bread during baking. *Food Research International, 42*, 865–870.

Sakin, M., Kaymak-Ertekin, F., & Ilicali, C. (2007). Simultaneous heat and mass transfer simulation applied to convective oven cup cake baking. *Journal of Food Engineering, 83*, 463–474.

Sakin-Yilmazer, M., Kemerli, T., Isleroglu, H., Ozdestan, O., Guven, G., Uren, A., et al. (2013). Baking kinetics of muffins in convection and steam assisted hybrid ovens. *Journal of Food Engineering, 119*, 483–489.

Schirmer, M., Jekle, M., & Becker, T. (2011). Quantification in starch microstructure as a function of baking time. *Procedia Food Science, 1*, 145–152.

Therdthai, N., Zhou, W., & Adamczak, T. (2002). Optimisation of the temperature profile in bread baking. *Journal of Food Engineering, 55*, 41–48.

Ureta, M., Olivera, D., & Salvadori, V. (2014). Quality attributes of muffins: effect of baking operative conditions. *Food and Bioprocess Technology, 7*, 463–470.

Vanin, F. M., Lucas, T., & Trystram, G. (2009). Crust formation and its role during bread baking. *Trends in Food Science & Technology, 20*, 333–343.

Xue, J., Lefort, G., & Walker, C. E. (2003). Effects of oven humidity on foods baked in gas convection ovens. *Journal of Food Processing Preservation, 28*, 179–200.

Zanoni, B., Peri, C., & Bruno, D. (1995). Modelling of browning kinetics of bread crust during baking. *Lebensmittel-Wissenschaft and-Technologie, 28*, 604–609.