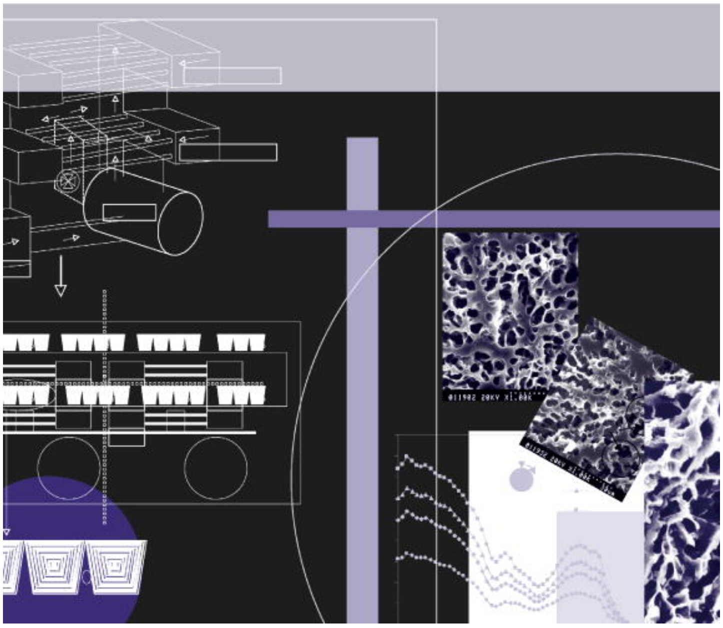
Volume 80, Issue 4

ISSN 0260-8774

journal of
food engineering



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ScienceDirect
Journal of Food Engineering 80 (2007) 1107–1115
JOURNAL OF FOOD ENGINEERING
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Bread browning kinetics during baking

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Received 18 July 2006; received in revised form 1 September 2006; accepted 2 September 2006
Available online 24 October 2006

Abstract

The development of browning at bread surface during baking is an important quality index. In this paper, the colour (CIE $L^*a^*b^*$ parameters) of bread surface was measured by computer vision. Also, the weight loss variation was determined during the process. Baking experiences were performed at 180, 200 and 220 °C under natural and forced convection. Linear trend was found between total colour change and weight loss of breads. A simple mathematical model was proposed to predict the development of browning during baking. The independent variables were the weight loss of breads and the baking temperature. For values of weight loss greater than 7%, the mean absolute estimation error of the proposed model was 6.23%.

Keywords: Colour change; Bread; Mathematical model

1. Introduction

Bread surface colour together with its texture and flavour are the main features considering consumer preference. Respect to regulation, the *Código Alimentario Argentino* (ANMAT, 2004) establishes that bread crust must present a uniform yellow-gold colour. Hence, the crust colour appears as a critical factor in the bread baking process.

The yellow-gold colour formation is often called browning. This transformation is due to chemical reactions producing coloured compounds during bread baking, specifically, caramelisation and Maillard reactions. Both reactions belong to the non enzymatic or non oxidative browning category (Fennema, 1993). Direct heating of carbohydrates produces complex reactions namely as caramelisation reactions. Whereas minimum substrates requirements for Maillard browning are the presence of an aminic compound, usually a protein, a reducing sugar and some water. The Maillard reaction is influenced by temperature, pH, moisture content, presence or absence of metallic cations, and inner sugar structure. Particularly, the reaction is accelerated at medium moisture level and high temperature (Fennema, 1993).

Detection methods for studied reactions include colorimetric observation at 420 or 490 nm, chromatographic separation, measurement of carbon dioxide evolution, UV and IR (infrared) spectrums analysis. However, these techniques are not so usefulness when colour changes need to be followed during food processing.

Shibukawa, Sugiyama, and Yano (1989) evaluated the effects of heat transport by radiation and convection in browning development of glucose–glutamate solutions and biscuits. In the solutions case, brown pigment formation was measured at 550 nm with a spectrophotometer and hydroxymethylfurfural (HMF) concentration was determined by the thiobarbituric acid (TBA) method, after heating at 180, 200, 220 or 240 °C. Biscuits were baked at

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doi:10.1016/j.jfoodeng.2006.09.007

200 °C for 5, 8, 13, 15 and 19 min, and then surface temperature and lightness were measured using a radiation thermometer and a colour difference meter, respectively. Shibukawa et al. (1989) demonstrated that colour development depended only on temperature: the higher was the surface temperature, the darker was the colour of the surface, independent of heat transfer mode. Furthermore, the development of brown pigment was a first order reaction.

Zanoni, Peri, and Bruno (1995) modelled browning kinetics of bread crust using dehydrated and milled bread crumb. Tests were carried out in a refractory plate at 140, 150, 165, 185, 210, 235 and 250 °C, while colour (as difference between initial and *t* time) was measured with a tristimulus colorimeter. The proposed model, following first order kinetics and dependent on surface temperature, was applied to predict crust browning during bread baking at 200 and 250 °C. Results were only acceptable at 250 °C.

In a similar way, Broyart, Trystram, and Duquenoy (1998) developed a first order kinetics model to predict lightness variation of biscuits surface depending on product temperature and moisture. Baking experiences were performed in a static electrical oven at 180, 210, 240, 270, 300 and 330 °C. Colour was evaluated using an infrared sensor. These authors reported an initial increasing and a posterior decreasing in the experimental values of lightness. Moreover, the darkening phase is initiated when surface temperature reached 105–115 °C. Model validation revealed relative errors between 1% and 24% at the end of baking (6 min).

Wählby and Skjöldebrand (2002) determined buns surface colour using a food analyser, which calculates the amount of reflected light through a black and white photo of the surface. Applying two different baking techniques (traditional and highly convective at low temperature), the authors concluded that crust browning development depended mainly on oven temperature. In addition, a linear trend between weight loss and browning was found for all baking configurations tested.

Bread surface colour was also used from a technological point of view. Therdthai, Zhou, and Adamczak (2002) established the colour of bread crust as a constraint in the temperature profile optimization during mould bread baking. Keskin, Sumnu, and Sahin (2004) used the colour change in bread as a comparison index between various baking systems. In both cases, browning of bread was measured with a conventional colorimeter.

Taking into account the importance of surface colour development in bread making, only few articles were published concerning browning kinetics modelling with prediction aims. Furthermore, the proposed models present dependence on surface temperature of bread, which is experimentally difficult to measure in an industrial continuous baking process/oven. For example, Zanoni et al. (1995) used two methods to determine surface temperature values: a (J type) thermocouple placed at bread surface and an infrared (IR) thermometer. However, these authors developed the browning model considering only the IR method since it produced higher temperatures values and the experimental error existing due to uncertainty in thermocouple position. Actually, correctly placing a thermocouple in the surface of a food is not an easy task, moreover, in the case of deformable and low consistency materials changing their volume during processing such as bread. But at the same time, it is quite risky to ensure the efficiency of the IR thermometer when is used through an oven window, which probably interferes in temperature measuring.

As was previously demonstrated, browning depends on surface temperature, but also showed an experimental correlation with weight loss during baking and with oven temperature (Wählby & Skjöldebrand, 2002). Bearing in mind that dehydration affects only the external zones (crust) of bread during baking (Wagner, Lucas, Le Ray, & Trystram, 2007; Zanoni, Peri, & Pierucci, 1993), weight loss appears as a good representation of the moisture variation at product surface. Therefore, the following hypothesis was established: the development of browning at bread surface during baking is dependent on weight loss.

With the aim of modelling browning kinetics, bread samples were baked at two different baking modes, *i.e.* natural and forced convection. Colour and weight loss measurements were performed during the process.

2. Materials and methods

2.1. Bread samples preparation

Samples were prepared using a standard recipe for French bread: wheat flour (100%), water (54.1%), salt (1.6%), sugar (1.6%), margarine (1.6%), and dry yeast (1.2%). Dough was made mixing the ingredients for 10 min in a home multi-function food processor at constant speed. Then individual samples of 100 g (*ca.* 0.1 m length, 0.04 m diameter) were formed and placed in a perforated tray. Proving was carried out at ambient temperature covering dough samples with a plastic film in order to prevent dehydration. After 1.5 h proving, samples duplicated their volume. Two (2) samples were prepared for each experiment.

2.2. Baking tests

Dough samples were baked in an electrical static oven (ARISTON FM87-FC, Italy) under natural and forced convection (0.3 m/s air velocity) conditions. Three baking temperatures were used: 180, 200 and 220 °C. Oven temperature was measured using T-type thermocouples (Omega, USA). The oven allows controlling temperature with ±3.3 °C accuracy. The tray with the samples (2) was placed in the central zone of the oven, which was under regime. Two tests were performed for each condition.

2.3. Weight loss determination

Weight loss during baking was determined by weighting the tray with the samples interrupting the process every 5 min. It is worth to note that this procedure took *ca.* 5 s, thus it was assumed that no significant perturbation was introduced in measurements. Weight loss (WL) was calculated as

$$\mathrm{WL}\ (\%) = \left(\frac{m_0 - m_t}{m_0}\right) x100 \qquad (1)$$

where m_0 was the initial weight (kg) and m_t was the weight (kg) at t (min) time of breads.

2.4. Crust browning measurement: computer vision

Computer vision (CV) was used to evaluate surface browning variation during bread baking. CV is an automated and cost-effective technique, which has already been applied to evaluate quality features of bakery products (Brosnan & Sun, 2004). This method is also non destructive and the measured surface size in a single determination is higher than that evaluated by a conventional colorimeter. Furthermore, the CV technique does not imply contact with sample, which is essential in deformable materials such as bread.

The CV system consisted in a digital camera (Professional Series Network IP Camera Model 550710, Intellinet Active Networking, USA) connected to a PC (AMD Sempron 2200+, 768 MB RAM). Images of bread surface were acquired under natural light conditions and the camera was located perpendicularly to bread surface at 0.4 m distance. It is worth to note that images were taken every 5 min, at the same times that weight loss was measured, since the CV system was built upon a balance (Fig. 1).

Next, image processing was performed. Each image consisted in a .jpg file, of 640 × 480 pixels resolution. Images were firstly trimmed keeping only bread samples surface, resulting in two rectangular images (Fig. 2a and b) for each determination. Then, an algorithm developed in Matlab 6.5 (The MathWorks, Inc., Natick, MA, USA) was used to calculate colour parameters. The CIE $L^*a^*b^*$ (or CIELAB) colour model was chosen to describe browning development. The CIELAB model is an international standard for colour measurement developed by the *Commission Internationale de l'Eclairage* in 1976 (Yam & Papadakis, 2004). The three parameters of such model represent the lightness of colour (L^*) which ranges from 0 to 100 (black to white), its position between red and green (a^*, values between −120 and +120) and its position between yellow and blue (b^*, values between −120 and +120). Since images were acquired in the RGB colour space, the following steps were carried out to obtain CIE $L^*a^*b^*$ model parameters:

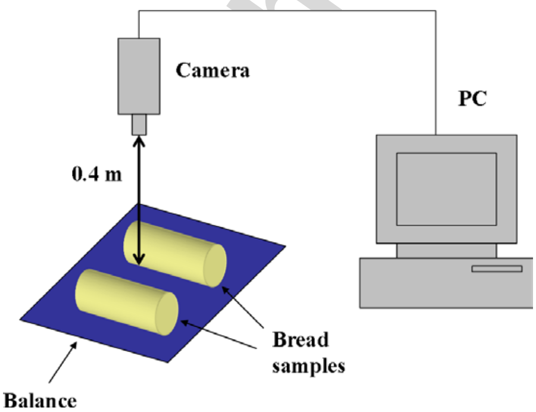

Fig. 1. Schematic diagram of the system used for simultaneous weight loss determination and images acquisition.

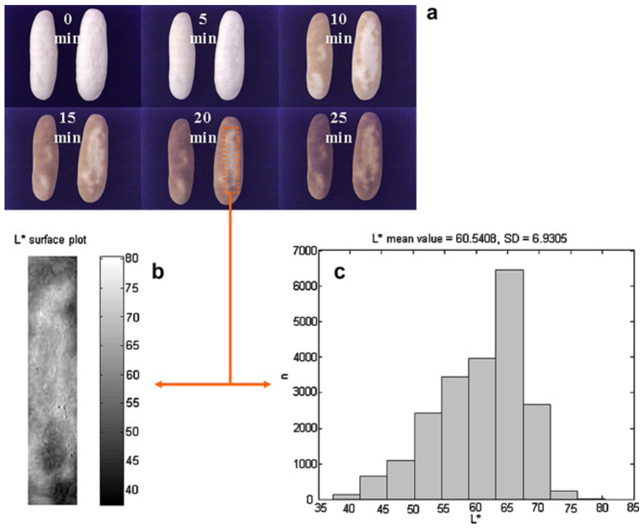

Fig. 2. (a) Image gallery of bread baked at 220 °C under natural convection at different baking times. (b) Surface plot of L^* value. (c) Histogram containing L^* mean value and standard deviation.

1. Image reading (in RGB space).
2. RGB to XYZ tristimulus space conversion.
3. XYZ to CIE $L^*a^*b^*$ space conversion.
4. Statistics of CIE $L^*a^*b^*$ parameters.

Conversion between colour spaces must be done using a white reference (Gonzalez & Woods, 2002). A perfectly reflecting diffuser under CIE standard $D65$ illumination was taken as white reference, which was defined through its trichromatic values ($x = 0.3127$ and $y = 0.3290$ in the CIE chromaticity diagram). Therefore, steps 2 and 3 were performed as following:

$$X = 0.4124g\left(\frac{R}{255}\right) + 0.3576g\left(\frac{G}{255}\right) + 0.1805g\left(\frac{B}{255}\right) \qquad (2)$$

$$Y = 0.2126g\left(\frac{R}{255}\right) + 0.7152g\left(\frac{G}{255}\right) + 0.0722g\left(\frac{B}{255}\right) \qquad (3)$$

$$Z = 0.0193g\left(\frac{R}{255}\right) + 0.1192g\left(\frac{G}{255}\right) + 0.9505g\left(\frac{B}{255}\right) \quad (4)$$

where

$$g(p) = \begin{cases} 100\left[\left(\frac{p+0.055}{1.055}\right)^{2.4}\right] & p > 0.04045 \\ 100[p/12.92] & p \leqslant 0.04045 \end{cases} \quad (5)$$

R, G and B are the RGB model components (values from 0 to 255). From tristimulus values (X, Y and Z), $L^*a^*b^*$ parameters were calculated as

$$L^* = 116\, h\left(\frac{Y}{Y_W}\right) - 16 \quad (6)$$

$$a^* = 500\left[h\left(\frac{X}{X_W}\right) - h\left(\frac{Y}{Y_W}\right)\right] \quad (7)$$

$$b^* = 200\left[h\left(\frac{Y}{Y_W}\right) - h\left(\frac{Z}{Z_W}\right)\right] \quad (8)$$

where

$$h(q) = \begin{cases} \sqrt[3]{q} & q > 0.008856 \\ 7.787q + 16/116 & q \leqslant 0.008856 \end{cases} \quad (9)$$

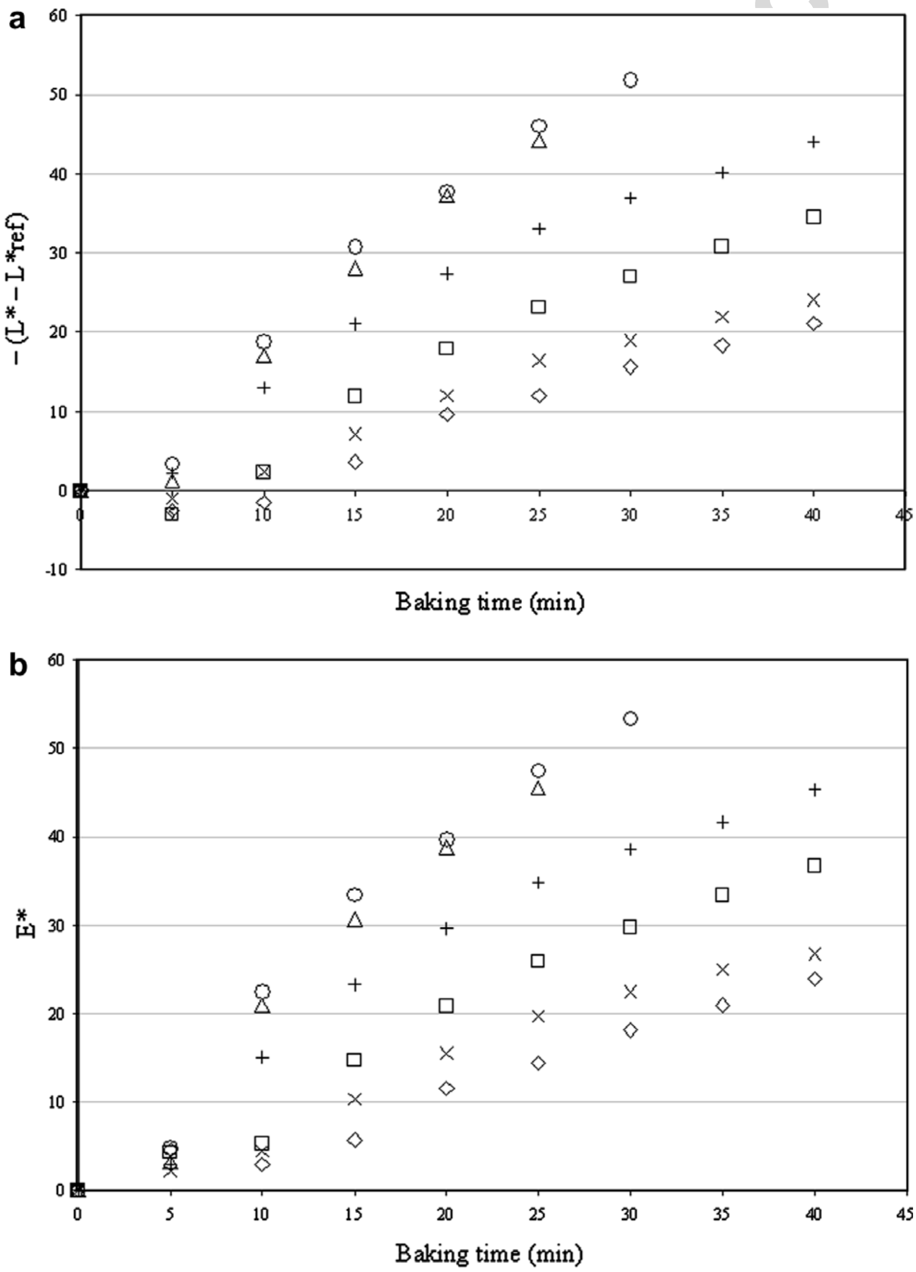

Fig. 3. (a) Variation of bread surface lightness (L^*), respect to raw dough (L^*_{ref}), during baking. (b) Variation of total colour change (E^*, Eq. (10)) of bread surface during baking. (◇) NC, 180 °C; (□) NC, 200 °C; (△) NC, 220 °C; (×) FC, 180 °C; (+) FC, 200 °C; (○) FC, 220 °C. NC: natural convection; FC: forced convection.

X_W, Y_W and Z_W are the reference white tristimulus values (Gonzalez & Woods, 2002). Statistics of $L^*a^*b^*$ parameters (step 4) included mean value, standard deviation and histogram calculation. Also, a surface plot of colour parameters of bread images could be obtained.

Once mean values of $L^*a^*b^*$ parameters were evaluated, the total colour change (E^*) was determined as

$$E^* = [(L^* - L^*_{ref})^2 + (a^* - a^*_{ref})^2 + (b^* - b^*_{ref})^2]^{1/2} \quad (10)$$

where L^*_{ref}, a^*_{ref}, b^*_{ref} were the reference values taken from unbaked dough (initial time of baking).

Before bread surface colour was measured, a calibration procedure of the CV system was carried out in order to ensure the validity of results. This was done using the calibrating plates of a conventional colorimeter (Minolta CR300, Japan) and adjusting the camera parameters. This calibration (similar to colorimeter calibration) was performed previous to each experience.

2.5. Modelling the browning of bread surface during baking

Colour development of bread crust during baking was mathematically modelled. Considering the established hypothesis, a simple model was proposed relating the total colour change (E^*) to weight loss (WL) as

$$E^* = k\mathrm{WL} \quad (11)$$

where

$$k = k_0 T_{oven} + k_1 \quad (12)$$

The proportionality constant k in Eq. (11) was named as rate of browning and was assumed dependent on baking

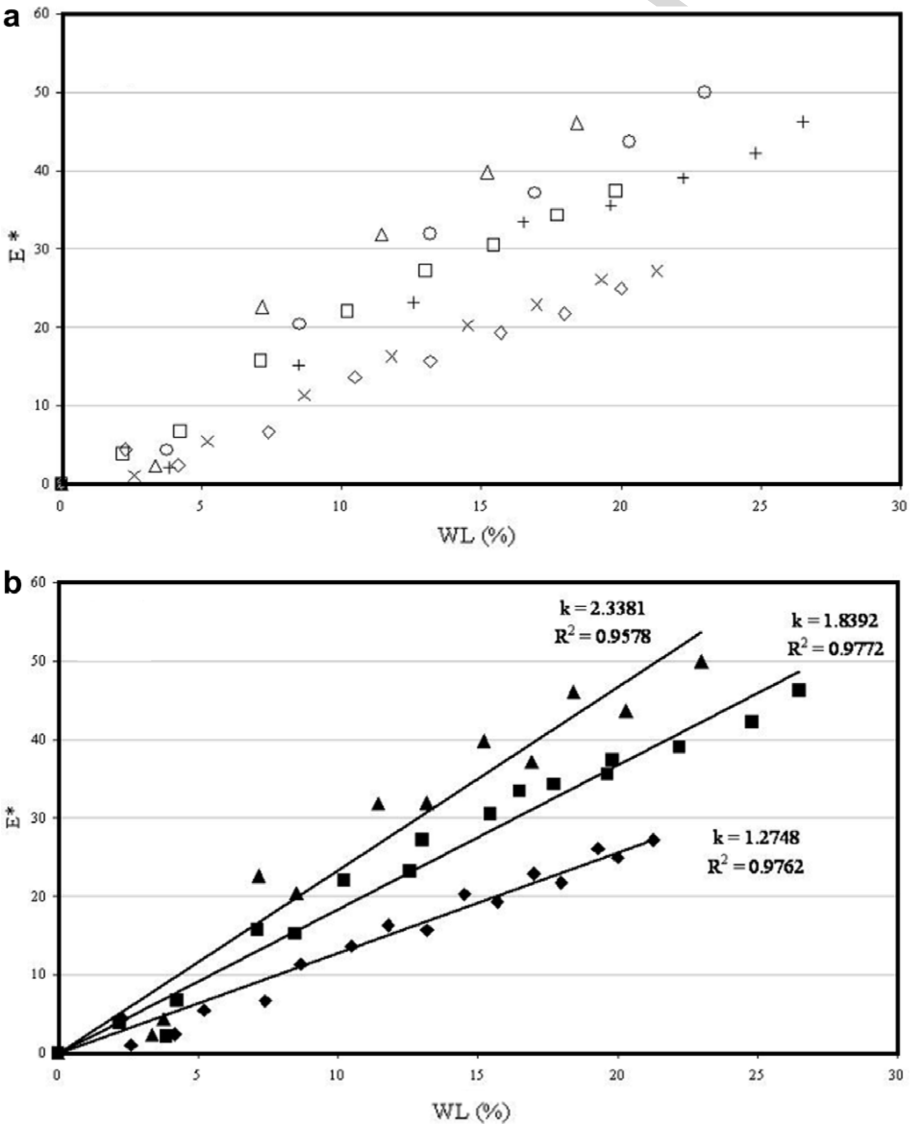

Fig. 4. (a) Variation of total colour change (E^*) of bread surface respect to weight loss (WL) of samples. (◇) NC, 180 °C; (□) NC, 200 °C; (△) NC, 220 °C; (×) FC, 180 °C; (+) FC, 200 °C; (○) FC, 220 °C. NC: natural convection; FC: forced convection. (b) Correlation between E^* and WL as a function of oven temperature only, and corresponding values of browning rate (k). (◆) 180 °C; (■) 200 °C; (▲) 220 °C.

temperature, T_{oven} (°C). Constants in Eq. (12), k_0 (°C^{-1}) and k_1, related the rate of browning to baking temperature. These model parameters were estimated using one set of experimental data, and the other set were used to validate the model.

The performance of proposed model was measured comparing experimental and predicted values. For this aim, the absolute relative error was defined as

$$\varepsilon\ (\%) = \left[\frac{|E^*_{\text{predicted}} - E^*_{\text{experimental}}|}{E^*_{\text{experimental}}}\right] 100 \qquad (13)$$

3. Results and discussion

Firstly, it may be noted the large amount of data processed by the CV method in a single measurement (Fig. 2). Fig. 2b shows the area selected for measuring the bread surface colour, where the mean value of L^* (Fig. 2c) was calculated over 21060 pixels. All colour information extracted through the CV method, as statistics on parameters $L^*a^*b^*$ and surface plot, would be almost impossible to obtain using the conventional colorimeter technique.

In agreement with Shibukawa et al. (1989), lightness of bread decreased as oven temperature was increased, independently of heat transfer mode from ambient to the product (Fig. 3a). At a same baking temperature, forced convection condition caused higher browning than natural convection situation, since the more rapid heating of bread surface (Fig. 3b).

As previous works, two stages could be distinguished in the variation of lightness with baking time, independently of oven temperature and convection mode. During the first minutes, the surface of bread showed an enlightenment respect to initial time (raw dough). This observation (at 180 and 200 °C under natural convection and 180 °C under forced convection) seems to be absurd, since this phenomenon is against browning development. Shibukawa et al. (1989) attributed this behaviour to surface drying, while Broyart et al. (1998) also proposed the contribution of initial volume change. Probably, the explanation is related to physical changes occurring at product surface. At the end of proving, surface of bread is wrinkled, irregular. But after a few minutes (2 or 3 min) of baking, the dough surface turns considerably smooth, may be due to volume increase. This change in surface texture could be the reason of initial enlightenment. It is well known that a smooth regular surface can reflect more amount of light than a wrinkled irregular surface.

The second stage is characterized by the darkening of bread surface due to Maillard and caramelisation reactions. Mainly, the formation of HMF in bread surface is responsible for browning development. Ramırez-Jiménez, Guerra-Hernández, and García-Villanova (2000) found an exponential correlation between HMF and baking time in bread, while HMF formation in cookies followed a first order kinetic (Ameur, Trystram, & Birlouez-Aragon, 2006). Finally, at the end of baking the lightness would tend to an asymptotic value corresponding to burnt sample (Zanoni et al., 1995).

In the same way as Wählby and Skjöldebrand (2002), a linear trend was found between the total colour change (E^*) and the weight loss (WL) of breads during baking. Moreover, this linear behaviour was similar at equal baking temperatures, independently of convection mode. No significant differences ($\alpha = 0.05$) were found between data obtained at the same oven temperature (Fig. 4). As can be seen from Fig. 5, correlation of the rate of browning (k) with oven temperature was almost perfect ($R^2 = 0.9987$), resulting in an accurate fitting of parameters of Eq. (12): k_0 (0.0266 °C^{-1}) and k_1 (−3.4991).

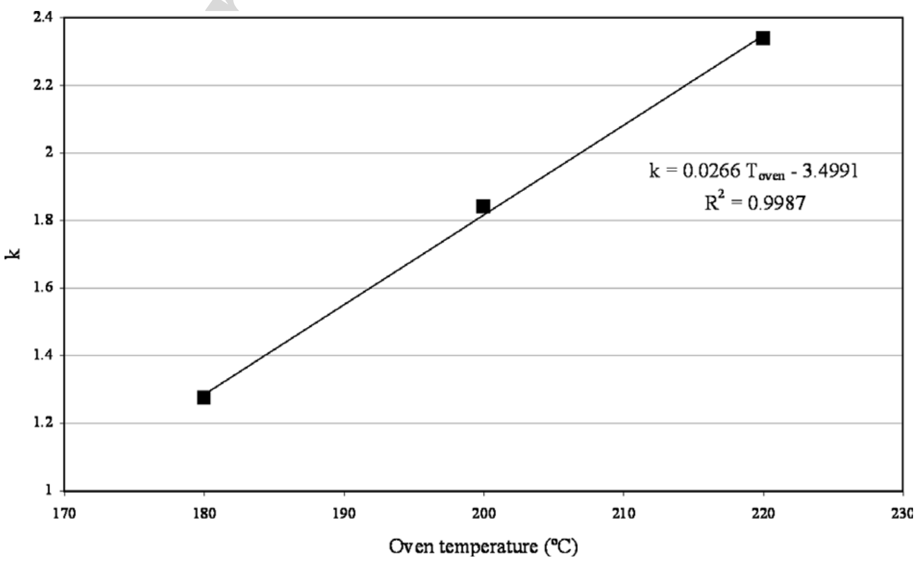

Fig. 5. Variation of the rate of browning (k) with oven temperature (T_{oven}).

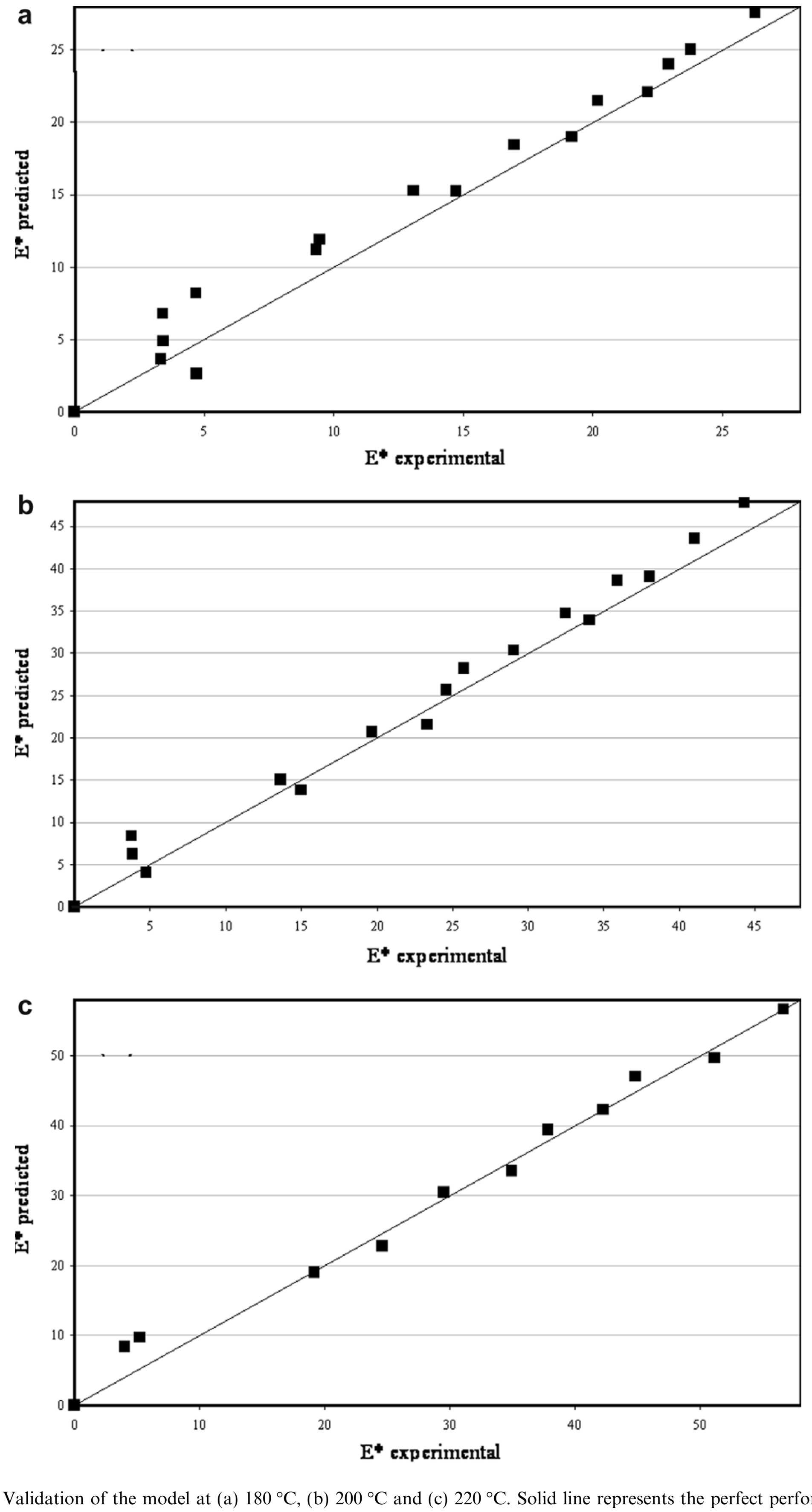

Fig. 6. Validation of the model at (a) 180 °C, (b) 200 °C and (c) 220 °C. Solid line represents the perfect performance.

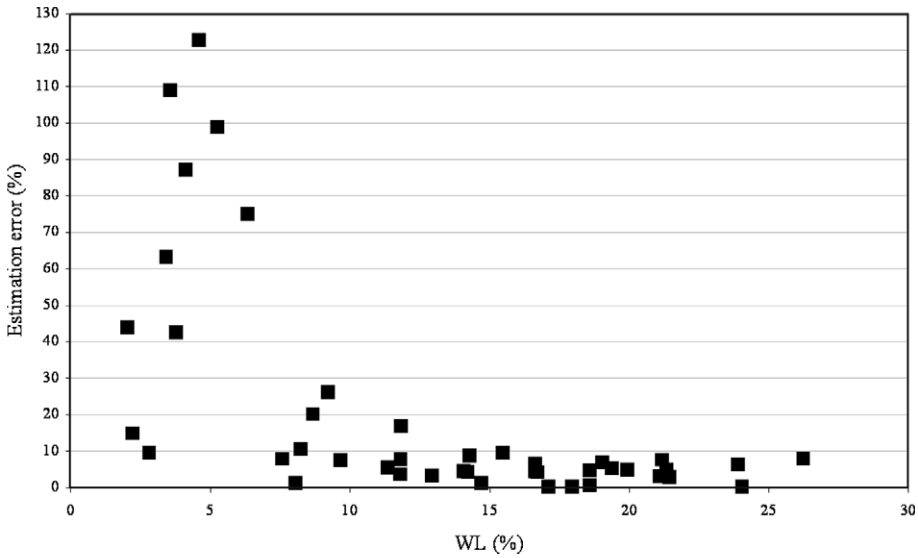

Fig. 7. Estimation error (Eq. (13)) as a function of weight loss (WL) of breads. All data used for validation are included.

Comparison between experimental and predicted values of E^* showed a good performance of the developed model (Fig. 6). However, the model produced high estimation errors (calculated by Eq. (13)) at low weight loss values (Fig. 7). This is probably due to non linearity of the first stage of browning, when a lag phase was observed. Before the darkening phase is initiated, the bread surface must reach the browning temperature set up, *i.e.* 105–115 °C (Broyart et al., 1998).

The relative errors for weight loss greater than 7%, which corresponded to 10–15 min of baking, were very acceptable. The mean relative error produced by the model was 6.23% for WL > 7% and 4.92% for WL > 10%. Previous experiments (results not shown) indicated that most of baking procedures last more than 10–15 min which is equivalent to WL > 7%. Estimation errors may arise from two main reasons. Firstly, bread surface images were taken under natural – not ideal – light conditions. This experimental aspect, attempting to reproduce real processing situations, could be source of additional noise in recorded images, reducing accuracy in subsequent colour parameters calculation. Secondly, average oven temperature values were included in the model, without intrinsic standard deviation. Nevertheless, the model developed here presents good accuracy to predict the total colour changes of bread during usual baking conditions. Furthermore, the independent variables chosen for modelling (weight loss and baking temperature) can be easily measured in any (continuous) industrial baking process.

4. Conclusion

The developed computer vision system demonstrated to be a useful tool to monitor the surface colour of breads during baking. In this work, a useful baking index such as surface browning was easily established by knowing the weight variation of breads and the baking temperature during the process.

Besides, a simple and accurate mathematical model to predict browning development during baking was presented, confirming that the development of browning at bread surface during baking is dependent on weight loss and oven temperature.

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