Article

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Water transport during bread baking: Impact of the baking temperature and the baking time

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Abstract

The impact of the baking temperature on the moisture profile (in terms of water content), during bread baking was analyzed using a convection oven (three oven temperatures and different baking times). During baking, local water content and temperature were measured at different regions of the crust and crumb. There was found an increase in water content at the core. Water content reached a maximum level (at about 2.5%), with no effect of the baking temperature, and decreased slowly at advanced baking times. Regarding the crust, a theoretical model relating water flux to the driven force (temperature difference between the oven environment and the vaporization front) and the crust thermal resistance was validated with experimental values. Water losses were also reported. The water lost by bread contributes significantly to the energy consumption by this process and its reduction is of concern for conducting the process in a more sustainable manner. A better optimization of heat transfer between the surface (for coloration purposes) and the core (for inflation purposes) could help in this way, together with shorter baking duration and hence higher yield.

Keywords

Water content, crust, crumb, heat pipe, evaporation–condensation–diffusion, dough

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INTRODUCTION

Breadmaking relies on four principal steps: mixing, proving/fermenting, baking, and cooling. Particularly, during baking the dough is transformed into a light readily digestible and flavourful product, due to a series of physical, chemical, and biochemical interactions, all of them with a strong dependence on temperature rise and moisture transport caused by oven heat (Vanin et al., 2013). Moisture transport proceeds by various modes: evaporation of surface water; diffusion of liquid water from the core to the surface; evaporation–condensation–diffusion (de Vries et al., 1989); Darcy flow of gaseous components through the open pores.

Most of the studies reported in literature focused on top crust and core crumb; the crust is often not precisely defined (Vanin et al. (2013) also highlighted the difficulty in defining this area) while the sampling of crumb is not free of bias, due to the evaporation of water from cut surfaces or the redistribution of water if sampling proceeds once the bread has been cooled (Wagner et al., 2007). Profiles or even maps with higher space resolution are scarce, often obtained in unusual geometries compared to the industrial concerns (Wagner et al., 2007; Zanoni and Peri, 1993), or

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available only at the end of baking (Besbes et al., 2013b). In consequence, most previous numerical models of baking focused on global mass balance (Nicolas et al., 2014; Purlis and Salvadori, 2009a; Papasidero et al., 2015; Zhang and Datta, 2006), missing to validate the multiple modes of water transport occurring locally. More recently, Lucas et al. (2015) developed a multiscale model of water transport by evaporation–condensation–diffusion using the gradient in partial vapor pressure in pores as driving forces. For the first time, simulated moisture profiles were compared to experimental ones, an increase in water content in the core was observed at the very beginning in both simulation and experiment, confirming evaporation–condensation–diffusion. However, while the experimental values returned back to the initial water content, the simulated ones maintained their values.

To our knowledge, the effect of the baking temperature on the total water loss and the inner water content distribution has not been previously reported. Therefore, an experimental study of bread baking was performed, using convection mode, three oven temperatures (low, medium, and high), and testing baking times between 1 and 75 min. At different regions of the crust and the crumb local water content and temperature were measured. Teachings for the conduction of the baking process in terms of product quality or energy savings were also drawn.

MATERIALS AND METHODS

Experimental procedure

Sample preparation. The flour was stored at −20 °C, defrosted at ambient temperature (20 °C) a few days before the experiment. Dough was prepared mixing 2000 g wheat flour (Inter-Farine), 90 g sugar (Daddy), 90 g colza oil (U), 40 g dry leavening (Saf-Instant), and 40 g improving agent (Améliorant PDM 2% Inter-Farine) for 90 s in a mixer (Moretti Forni Spiry 8, Italy) at 100 r/min. After that, 1060 g water and 0.03 g ascorbic acid were added and mixed for 240 s more. Once dough was formed, 36 g salt (La Baleine) was incorporated and mixed for 360 s more. The final temperature of the dough was 21 ± 1 °C. A dough piece (250 ± 1 g) was then rounded and left 20 min at ambient temperature. After that, the dough was stretched manually in order to achieve square shape (28×28 cm^2). The piece of dough was rolled and was cut into four pieces of even size (7 cm long), which were placed into the glass mold with 90° turn compared to the axis of the original roll. The glass mold (rectangular dimensions $200 \times 70 \times 70$ mm^3) was previously coated with Teflon to reduce adherence. The sample was proved in a proving chamber (BONGARD BFA 400 × 600, France) with highly humidified air (85% relative humidity) at 35 °C for about 55 min. A piece of dough (25 g) was placed in a tester in the same conditions as the dough to be baked, the mold was taken out the proving chamber once it was checked that the tester volume had been tripled.

Bread baking. The sample was baked in a convection oven compatible with continuous MRI measurement (Wagner et al., 2008). Given the oven operational characteristics, air velocity at the level of the mold was 3 m/s and air temperature beneath the plate is about 10°C lower than ahead the mold.

Baking tests were carried out at 142 ± 4 °C (low baking temperature, LBT), 185 ± 4 °C (mid baking temperature, MBT), and at 210 ± 4 °C (high baking temperature, HBT), values which refer to the air temperature ahead of the mold; it took between 120 and 180 s to reach these values. The baking time was prolonged beyond the point of optimal baking to enhance the comparison between different baking conditions (more details in Appendix). Separate runs were carried out for temperature and dry matter measurements. In the former case, the position of each fiber was checked after baking. In the latter case, baking was interrupted at different baking times: 1, 2, 3, 6, 12, 15, 20, 22, 25, 30, 45, and 75 min, and, before sampling for dry matter measurements, the whole bread was pictured (top view) with a digital camera and was weighted to calculate the total water loss. Both measurements (temperature and dry matter) were performed at the same position in the length direction of the bread loaf (Figure 1(a) and (b)).

Sampling times at 6, 12, 20–22, and 45 min were repeated two to four times (3–5 runs) for all baking temperatures; other ones were sometimes repeated once, less often twice (1–3 runs).

Sampling. Before cooling the loaf, a slice about 20 mm thick was cut from the middle of the third roll (Figure 1(a)). First of all, from this slice were taken out the "top zone" and the "bottom zone" to get a "crumb zone". This crumb zone was processed first and divided into three regions: upper, core, and lower crumb. The height of each region was measured with a calliper. Secondly, top and bottom zones were analyzed. The coloration and hardness served for the splitting into smaller regions. At the top, the soft crumb attached to the crust (upper$^+$ crumb) was separated from the harder part, the latter being separated again into brown and white top crust samples. At the bottom, the white part was simply separated from the brownish part: brown versus white bottom crust. The whole sampling procedure lasted no more than 5 min. It is important to remark that at short baking times, there could

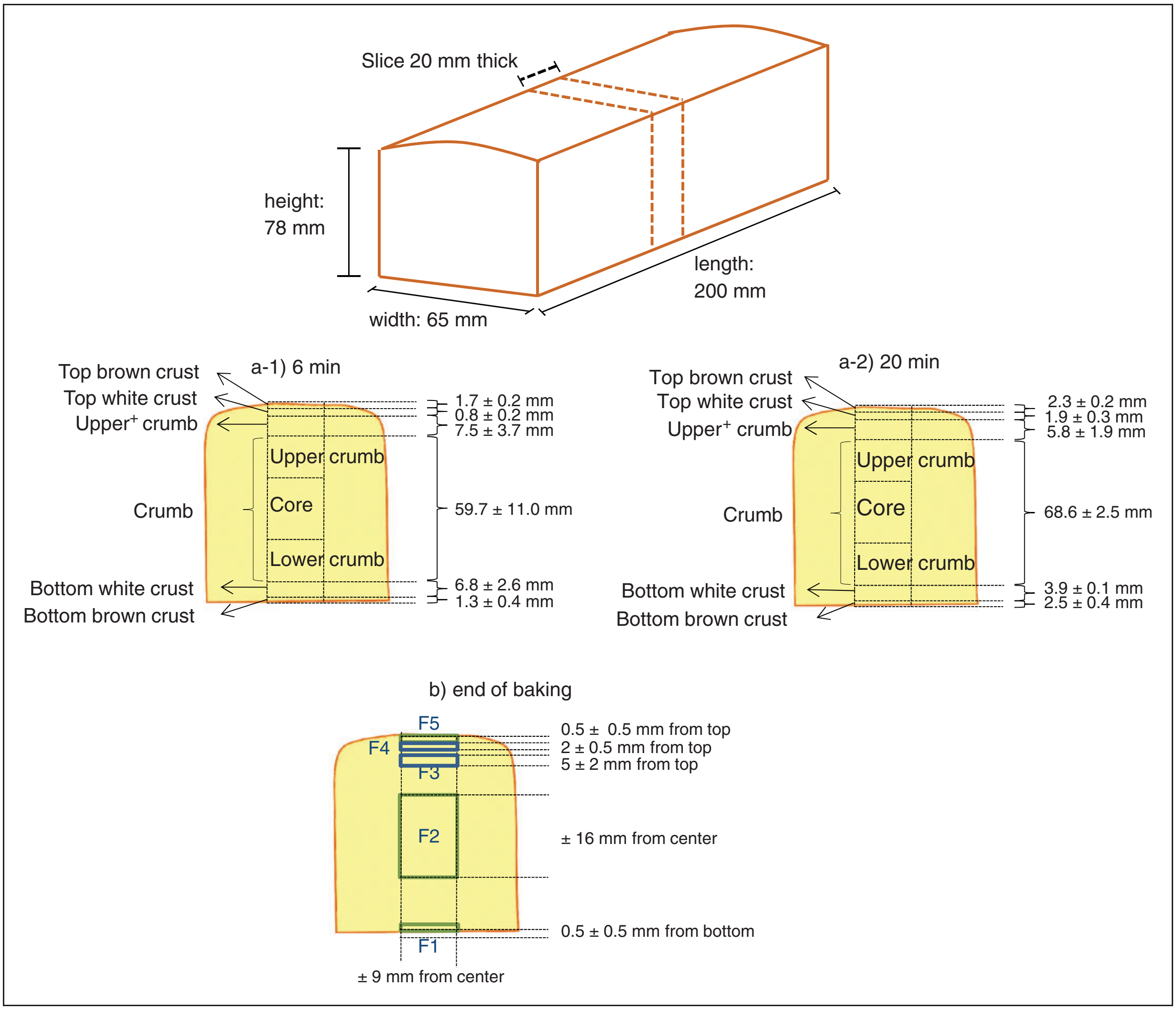

Figure 1. (a) Crust and crumb regions. (b) Positions of the fibers inside bread slice.

only be distinguished three regions: top crust—unbaked crumb—bottom crust.

Temperature measurement. Inner bread temperature was measured with FISO optic fibers (FISO UMI-8 datalogger with FISO FOT-L fibers) connected to a PC and recorded every 5 s.

Fibers were positioned at different heights (Figure 1(b)): bottom brown crust ($F1$), core ($F2$), upper^{+} crumb ($F3$), top white crust ($F4$), and top brown crust ($F5$). Positions were checked after baking with a calliper. For the core position, the bread was gently cut and the crumb was taken out with tweezers to access the fiber without shifting it.

Data analysis

Water loss (WL, %) was measured at each sampling time according to equation (1) where $m_{loaf}(t)$ is the mass of bread loaf at time t

$$WL = 100\,\frac{\left(m_{loaf}(0) - m_{loaf}(t)\right)}{m_{loaf}(0)} \tag{1}$$

Note that equation (1) assumes that water evaporation is the only component that affects mass loss during baking.

Water content (WC_{wb}, kg of water per 100 kg of crumb/crust wet basis) was calculated according to equation (2), where m_{r_0} and m_{r_24} are the mass of each sub-region before and after drying in a convective oven (103 °C, 24 h), respectively.

$$WC_{wb} = 100\,\frac{(m_{r\_0} - m_{r\_24})}{m_{r\_0}} \tag{2}$$

It was also expressed on dry basis (WC_{db})

$$WC_{db} = \frac{WC_{wb}}{(100 - WC_{wb})} \tag{3}$$

Total water flux was estimated from the experimental data using equation (4) and expressed in kg of water per kg of dry matter (m^2/s)

$$\dot{m}^{exp}_{w\ surf}(t) = -\frac{1}{S_{top\ surf}\left(m_{loaf}(0) - m_{w\ loaf}(0)\right)} \times \left[\frac{m_{w\ loaf}(t) - m_{w\ loaf}(t - \Delta t)}{\Delta t}\right] \tag{4}$$

where $S_{top\ surf}$ is the top surface of the bread loaf and $m_{w\ loaf}(t)$ is the mass of water in the bread loaf at time t

$$m_{w\ loaf}(t) = WC_{wb}(0)\ m_{loaf}(0) - \left(m_{loaf}(t) - m_{loaf}(0)\right) \tag{5}$$

The rise in total pressure inside the product was always low compared to the atmospheric pressure (Grenier et al., 2010). This means that once the dough films were ruptured, leading to a connected porous structure; the transport of water vapor through the dry zone was not a limiting factor. Since the bread core was still wet (water activity close to 1), the temperature at the evaporation front was therefore close to 100°C. The energy balance in the dry zone considering that all the energy input serves the vaporization of water at the evaporation front, can hence be described as follows

$$L_{w100}\dot{m}^{theo}_{w\ surf} \cong \frac{T_{baking} - T_{eb}}{\frac{e_{dry}}{\lambda_{dry}} + \frac{1}{h}} \tag{6}$$

where L_{w100} is the latent heat at 100°C (2257×10^3 J/kg), $\dot{m}_{w\ surf}$ is the the total water flux at the top surface, $T_{baking} - T_{eb}$ is the temperature difference between the vaporization front and the environment in the oven, e_{dry} and λ_{dry} are the thickness and the thermal conductivity (0.2 W/m·K) of the dried crust respectively, and h is the external heat transfer coefficient (35 W/m^2·K). In other words, the thermal resistance $\frac{e_{dry}}{\lambda_{dry}} + \frac{1}{h}$ in the right term of equation (6) governs the rate at which water vaporizes.

RESULTS AND DISCUSSION

Water migration in and transfer from the loaf to the oven atmosphere were characterized dynamically and presented in the following, proceeding from the highest to the lowest scales: water loss at the scale of the bread loaf, and moisture profiles with a space resolution variable from the millimeter (in the crust) to the centimetre (at core).

This study was completed with measurements of dough temperature and images of the top bread surface to qualitatively evaluate superficial color. In this sense, baking is judged to be optimal when the crust is sufficiently colored and the transition from dough to crumb (at about 95°C) is achieved at core. Given that coloration of the crust under convection conditions was a longer process than heating at core (Appendix), the former was used for defining the optimal baking times; 45 min for LBT, and 20 min for both MBT and HBT. Nevertheless, because these topics have been the object of numerous past studies and since they are aside the main objective of the present paper, the associated data are shortly presented and discussed in the Appendix section.

Water loss

Figure 2 shows WL evolution for different baking temperatures. In all cases, WL increased linearly up to 4–5% at early times (stage I), and then was followed by an exponential increase (stage II), which slowed down its rate at prolonged baking times. Relative error was high for sampling times lower than 15 min (10–15%), and low for longer baking times (<5%); this was due to the experimental difficulty to manipulate partially baked samples.

The slope in stage I slightly increased with increasing baking temperatures. Whatever the baking temperature, transition between stages I and II (vertical lines, Figure 2) coincided with the temperature profile becoming flat in the crumb (95°C at the core, section A1). Below this point, heat served to increase temperature (sensitive heat) and beyond this point, it was fully used to vaporise water (latent heat), accordingly with Zhang et al. (2017). Results from the present study verified that the lower the baking temperature, the longer the duration of stage I was. According to Figure 3, equation (6) represents quite well the trend of the experimental total water flux during stage II (equation (4)). Yet Zhang et al. (2017) partly validated this; in the present work, both T_{baking} and λ_{dry} present in equation (6) were at play—indeed, MRI monitoring showed that the top and bottom crusts were denser with higher baking temperature (data not shown), impacting the thermal conductivity in these areas.

Figure 4 presents WL evaluated at optimal baking times. Average value of WL was $11.8 \pm 1.3\%$, consistent with values expected for pan bread (Marston and Wannan, 1976). Compared to MBT, WL increased at

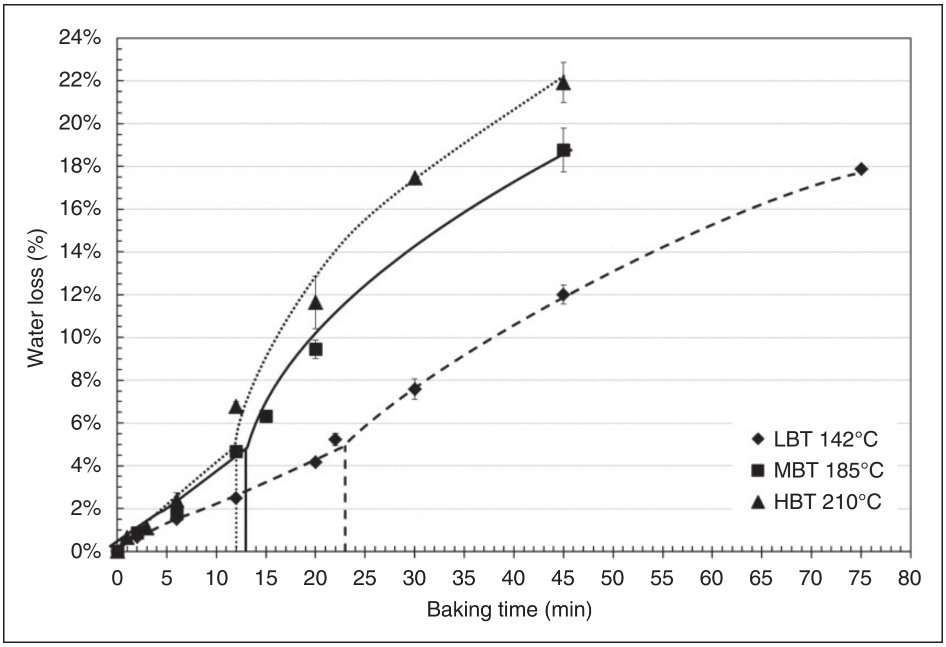

Figure 2. *WL* vs. baking time; effect of the baking temperature.
LBT: low baking temperature; MBT: mid baking temperature; HBT: high baking temperature.

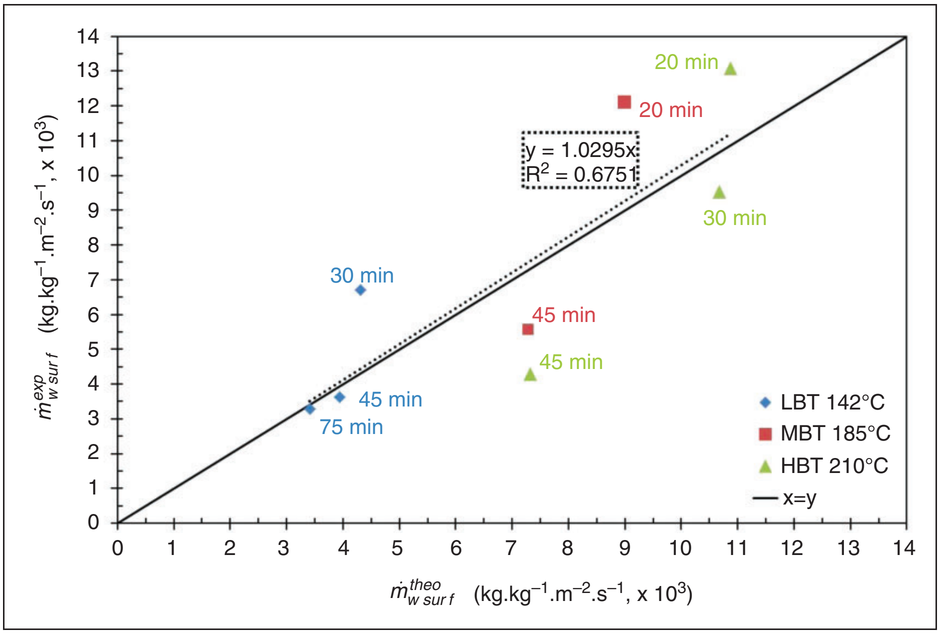

Figure 3. Total water flux relative to the mass of dry matter estimated from experimental data (equation (4)) and predicted by equation (6); effect of the baking temperature.

low baking temperature as often predicted from industrial practices. On the other side, crust coloration at HBT was faster than at MBT, but also more heterogeneous (Figure 9), hence requiring an optimal baking time equal to MBT. So *WL* at HBT was also higher compared to MBT.

Note that for all baking temperatures, stage II was well developed, leading to accelerated *WL*. In comparison, *WL* values obtained at the transition times between stages I and II were much lower (around 6%), presenting a slight increase as the baking temperature increases (Figure 4).

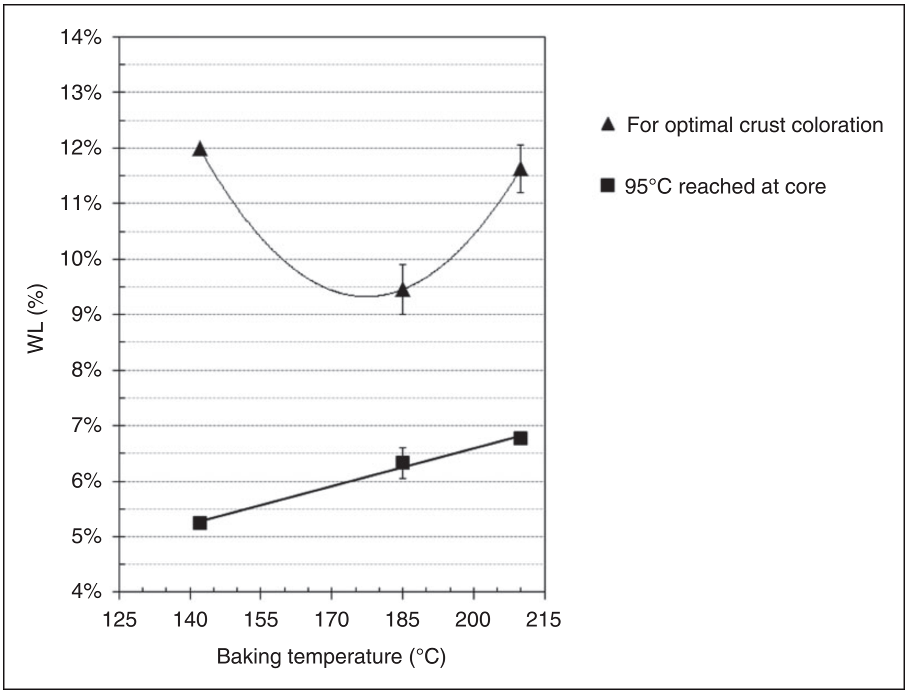

Figure 4. *WL* at different stages of baking.
LBT: low baking temperature; MBT: mid baking temperature; HBT: high baking temperature.

According to the results of "EU-FRESHBAKE" European Project, baking is one of the most energy demanding processes. In conventional baking, the energy consumption related to the evaporation of water represents about 23–26% of (Le Bail et al., 2010). In consequence, reducing *WL*, and more particularly the duration of stage II is crucial to reduce energy consumption.

From our knowledge, stage II often lasts 5–10 min at the industrial scale, this resulting from the zoning of oven tunnels, the first zone being devoted to the oven-rise, hence limiting the dehydration of external surfaces, the second zone devoted to crust coloration, hence accelerating the dehydration of the external surfaces. Because we used a convection oven, the same trend was observed in the present study. Accurate characterization of the cessation time for oven-rise, and its synchronization with higher heat flux could be a strategy for improvement.

Water distribution through the dough

Figure 5 presents the evolution of WC_{wb} in each subregion indicated in Figure 1 for the reference condition MBT (Figure 5), for which sampling times and repetitions per sampling time were the highest. As expected, both brown crusts (top and bottom) presented a more significant decrease in WC_{wb} (<10% at the end of baking). On the contrary, and consistently with previous reports for core crumb only (Purlis and Salvadori, 2009a; Thorvaldsson and Skjöldebrand, 1998; Wagner et al., 2007; Zanoni and Peri, 1993), the whole crumb region maintained or even increased their WC_{wb}.

In the following, the effect of the baking temperature at different specific locations (Figure 6) is discussed. WC_{wb} is also plotted as a function of their local temperature when available (Figure 7).

Top crust. Results in Figure 6(a) showed that the higher the baking temperature, the drier the top crust. WC_{wb} at 45 min was 9.5%, 5.6%, and 3.7% for LBT, MBT, and HBT, respectively.

The same WC_{wb} data plotted against local temperature in the top crust (Figure 7(a)) almost superimposed, whatever the baking temperature, meaning that differences in Figure 6(a) are only time-dependent. At prolonged baking times, the drying rate slowed down and the hydrothermal pathways diverged; both features were due to the approach of their respective oven temperature set.

Crumb, especially crumb at the very core. WC_{wb} in core crumb (including zones neighboring the core) increased during baking (Figure 6(c) and (e)). Maximum increase in WC_{db} in core crumb was 6.0–7.0%, observed, as expected, at baking times close to

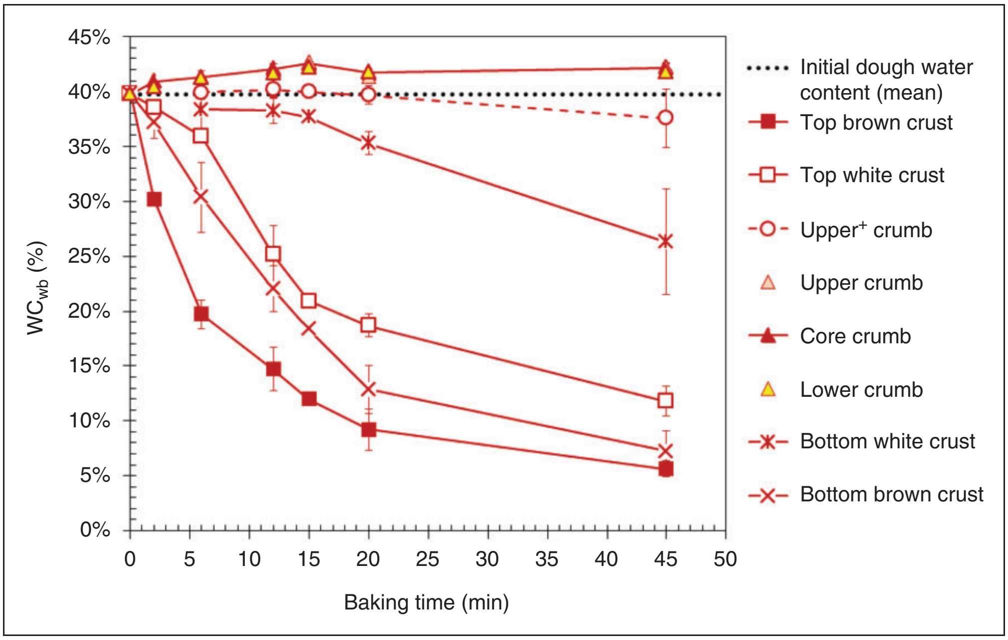

Figure 5. *WC_{wb}* at different locations in the dough (MBT baking temperature).

the transition between stages I and II (the flux by evaporation–condensation–diffusion decreases to zero as the temperature gradient in crumb becomes nihil).

The influence of time elapsed during the crumb sampling procedure was tested (Figure 6(d)). In a few trials, crumb sampling was delayed until the crust samples were separated from the loaf and weighted; while in the rest of them crumb sampling was done immediately after cutting off the loaf slice. The results confirmed that water gained at core during baking almost totally vanished within a few minutes in contact with the ambiance.

The mass of water taken up relative to the crumb dry matter was also calculated (Figure 6(d) and (f)), and did not differ between the different baking temperatures; nevertheless the lower the heating rate, the longest the time needed to reach such values was. In this sense, the water flux to the core is governed by the gradient in temperature between the evaporation front and the temperature at core (Lucas et al., 2015). The former temperature is independent of the baking temperature, while the latter increased more slowly for LBT (section A1). As expected, the temperature–WC curves at core crumb superimposed whatever the baking temperature (Figure 7(c)). The pathway demonstrated that dehydration practically does not occur during baking in this region, these curves start with the proving temperature and the initial WC_{wb}, and stop at the temperature of water ebullition (about 100°C) with the almost same, even higher, WC_{wb}.

Thorvaldsson and Skjöldebrand (1998) applied near infrared (NIR) for monitoring water content during baking, only for advanced times due to the sensor sensitivity. Wagner et al. (2007) reported an increase in core crumb water content at initial baking times, shorter than 7 min; the authors suspected that the dehydration of samples at longer baking times affected the measurement. Earlier reports (de Vries et al., 1989) concerned measurements performed on crumb sampled after cooling, with a non-negligible contribution of water equilibration within the bread loaf. To our knowledge, this is the first time that the dynamics of water increase in dough core during baking, also at advanced baking times, is reported with reduced experimental bias. These results confirmed the evaporation–condensation–diffusion mechanism (de Vries et al., 1989), and are consistent with the numerical simulation of baking process presented in Lucas et al. (2015).

Bottom crust. WC_{wb} in the bottom crust presented similar trends as in the top crust: it decreased exponentially with baking time (Figure 6(b)). Similar values of WC_{wb} were achieved at long baking times (13%, 7.25%, and 4.75% at 45 min for LBT, MBT, and HBT, respectively). In the bottom crust, heating was slightly faster than dehydration during the first stage of baking, as can be seen from the WC_{wb} data plotted against local temperature (Figure 7(b)). Once again, the curves for different baking conditions are

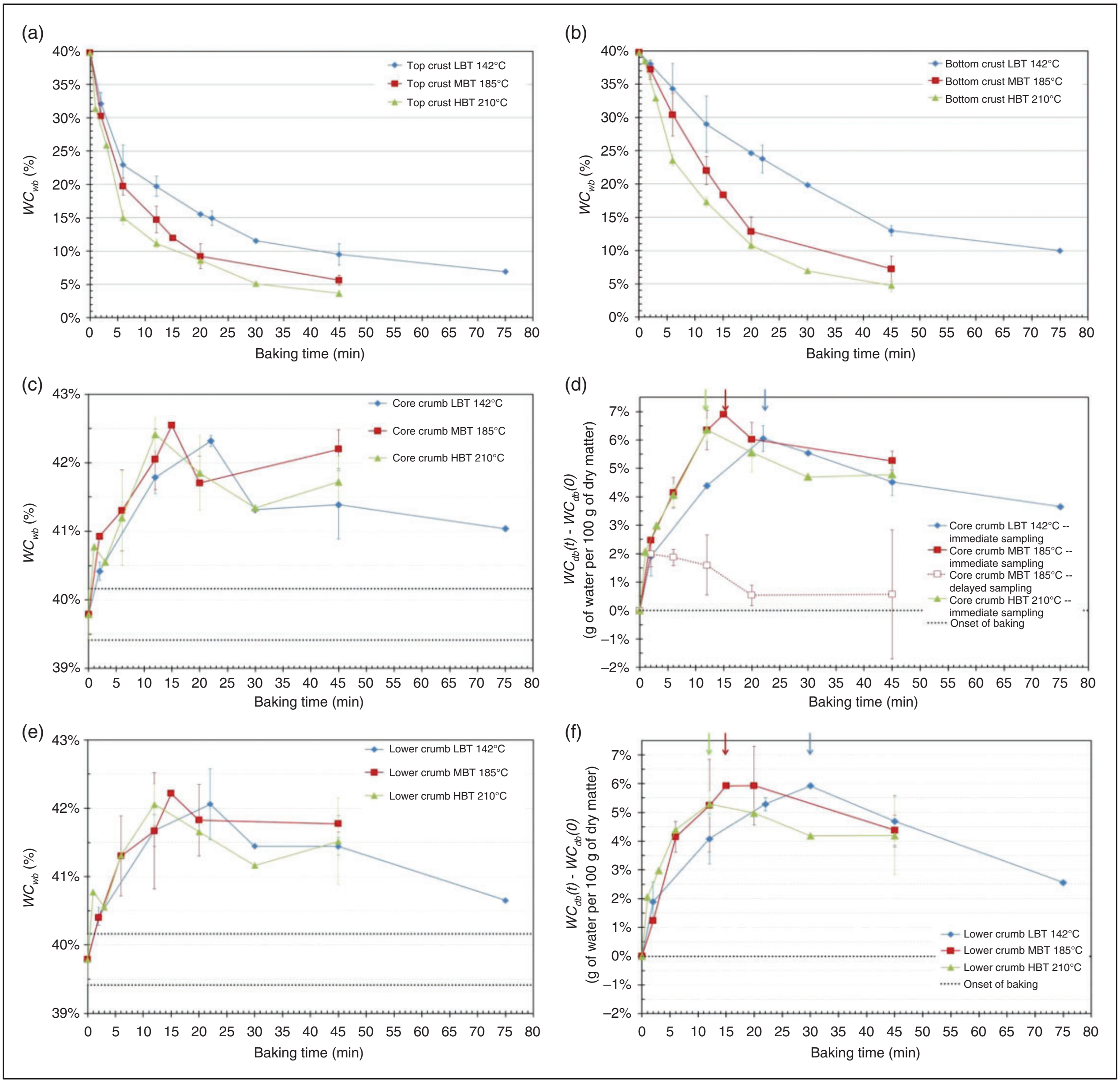

Figure 6. WC_{wb} in the top (a) and bottom (b) crusts and WC_{wb} and WC_{db} in core (c, d) and lower (e, f) crumbs. Arrows in (d, f) indicate the time of maximum amount of water.
LBT: low baking temperature; MBT: mid baking temperature; HBT: high baking temperature.

superimposed, meaning that differences in Figure 6(b) are only time-dependent.

Thorvaldsson and Skjöldebrand (1998) proposed that, since the gases could not diffuse from the surfaces in contact with the mold, the evaporated water moved towards the colder regions (center) by the heat pipe mechanism; this was recently confirmed by numerical simulations in Lucas et al. (2015). In the present study, dehydration in the bottom crust persisted beyond the cessation of the heat pipe mechanism (coinciding with the attainment of the temperature of water ebullition at core), suggesting that other types of water transport must be considered. First, water may be transported (by diffusion and/or convection) along the crust layer towards the top of the mold. Second, because of loaf shrinkage, a gap can appear between the internal surface of the mold and the bottom and lateral surfaces of the loaf, favouring the escape of vapour. Indeed, loaf shrinkage at MBT was observed by MRI from 11 to 12 min of baking (data not shown).

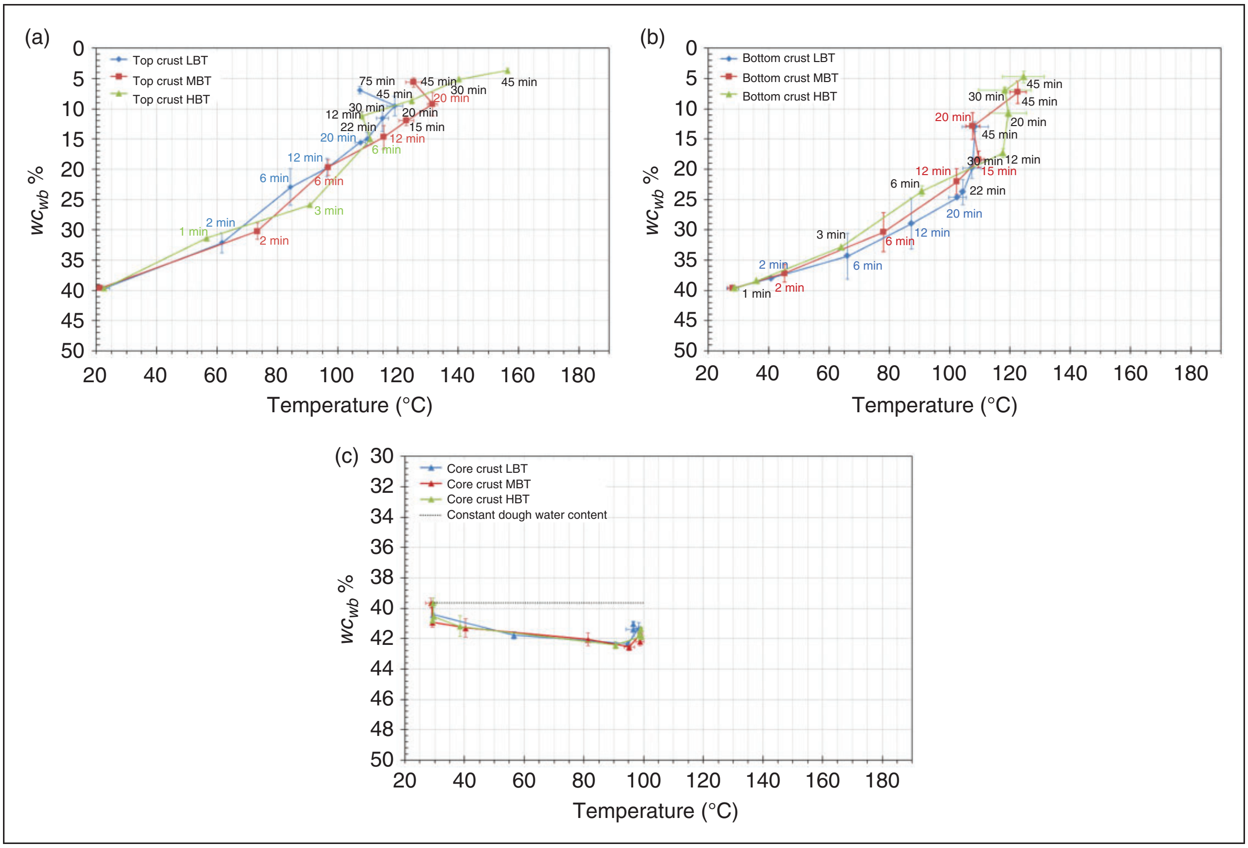

Figure 7. WC_{wb} in the top (a) and bottom (b) brown crust, and at core in crumb (c) vs. local temperature. LBT: low baking temperature; MBT: mid baking temperature; HBT: high baking temperature.

CONCLUSION

In the present work water content in bread crumb during baking was monitored continuously, enabling the recording of an increase at the core with minimal bias. This fact was consistent with the heat pipe mechanism: water accumulated at core during the first part of baking, while the temperature gradient in the dough was pronounced. Maximal gain in water content was up to 2.5%, without influence of the baking temperature. This is the first time that the dynamics of water increase in dough core during baking is reported from the entrance of the oven up to the point where temperature gradient in crumb is vanishing, offering a more precise characterization of the evaporation–condensation–diffusion mechanism applied to bread dough.

Regarding the crust, where an important dehydration was measured, this study validated a simple model relating water loss to the thermal resistance of the dry zone and the difference between the baking temperature and the temperature at the evaporation front. Also, the rate of *WL* steeply increased once temperature profiles in crumb were rather flat, close to water ebullition temperature (stage II). This study proposed to consider the transition to stage II when defining the optimal baking time; this will allow reducing mass loss, concomitantly improving product quality (softer crumb) and energy savings.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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APPENDIX

A1 Dough temperature

Figure 8 shows temperature profiles measured at different heights in dough baked at LBT, MBT, and HBT temperatures, these curves were similar to those already reported in the literature (Marston and Wannan, 1976; Purlis and Salvadori, 2009a; Thorvaldson and Skjöldebrand, 1998; Zhang and Datta, 2006). Transition from dough to crumb is usually completed at 95 °C, temperature reached at 23, 15, and 13 min for LBT, MBT, and HBT, respectively. From this point the temperature profile became rather flat and it stabilized when the water ebullition temperature is reached, as it is shown in Figure 8.

A2 Color of the bread top surface

Crust color was analyzed in a qualitative manner using digital photos (Figure 9). Initially dough surface had a creamy white color and as baking progressed, the gold brown color, typical of this kind of products, appeared. A combined effect of baking temperature and baking time was noticeable, as already discussed by Purlis and Salvadori (2009b), notwithstanding, darker color was obtained at the same baking temperature in this study due to the use of forced convection instead of natural one. Bread loaves were very dark after 25 min and 20 min of baking for MBT and HBT conditions, respectively. On the contrary, LBT condition showed an acceptable color level even at prolonged baking times (75 min).

A3 Optimal baking times

Baking is judged to be optimal when the crust is sufficiently colored and the transition from dough to crumb

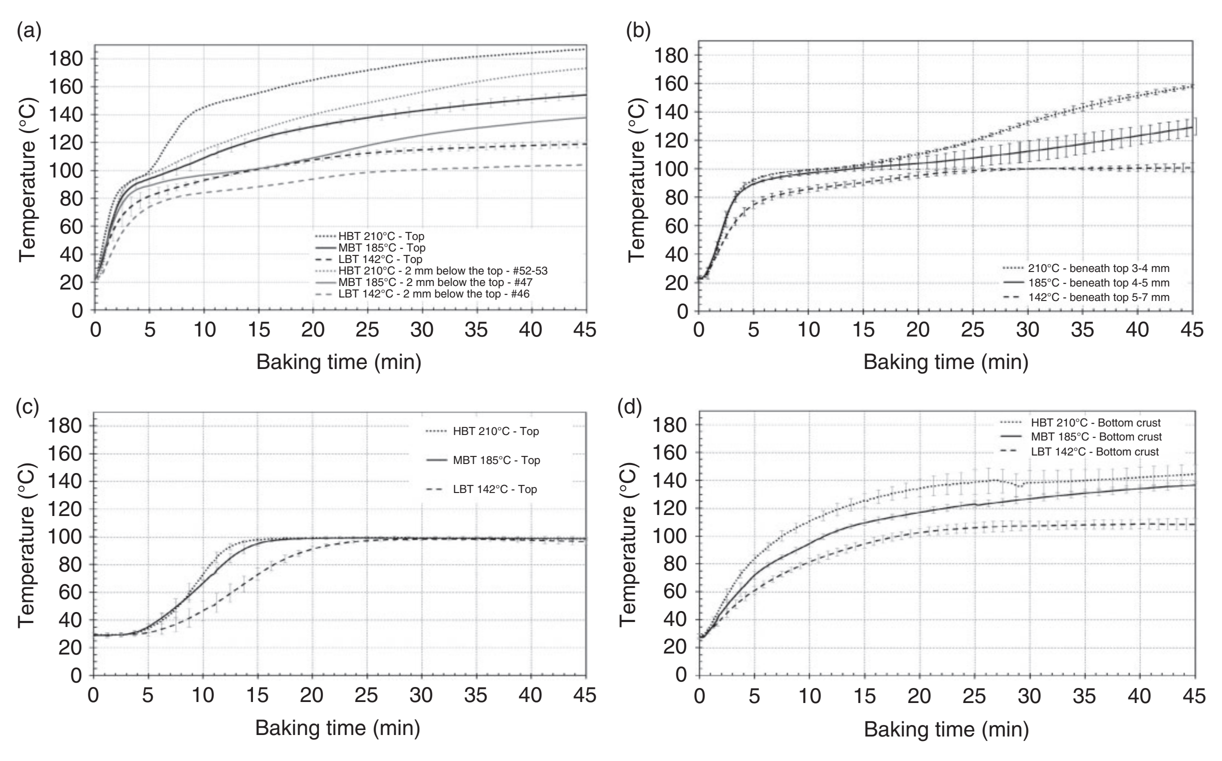


Figure 8. Temperature profile at (a) top crust and 2 mm beneath the top surface, (b) about 5 mm beneath the top surface, (c) core crumb, (d) bottom crust.
LBT: low baking temperature; MBT: mid baking temperature; HBT: high baking temperature.

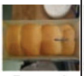
	1 min	2 min	3 min	6 min	12 min	20 min	25 min	30 min	45 min	60 min	75 min
LBT	No trial	 Dough 72	No trial	 Dough 9	No trial	 Dough 12	 Dough 32	 Dough 71	 Dough 46	 Dough 50	 Dough 77
MBT	No trial	 Dough 60	No trial	 Dough 19	 Dough 23	 Dough 20	 Dough 33	No trial	 Dough 47	 Dough 48	No trial
HBT	 Dough 58	No trial	 Dough 81	 Dough 16	No trial	 Dough 24	 Dough 8	 Dough 54	 Dough 14	 Dough 52	No trial

Figure 9. Images of the top surface of the bread loaves, combined effect of the baking temperature and the baking time.

is achieved at core. Not overpassing the optimal baking time is also critical to reduce the investment costs (size of the oven) or maintain high production yield. In this study, coloration of the crust was a longer process than heating at core and was hence used for defining the optimal times: 45 min for LBT and 20 min for both MBT and HBT. For comparison, these times were 22, 5, and 7 min less, respectively, that those obtained for the dough/crumb transition. Note that color was not comparable between the different baking temperatures. Nevertheless, earlier baking times at HBT could not be retained because the coloration was uneven, and as the color changes at LBT were slow, significant color change was not observed with longer baking times.