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Bread baking as a moving boundary problem. Part 1: Mathematical modelling

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Abstract

A mathematical model for the bread baking process is developed in this work. Experimental data (temperature, water content, weight loss, crust thickness) obtained during baking is used to well understand the simultaneous heat and mass transfer occurring during the process. The evaporation-condensation mechanism is responsible for the rapid heating of the porous matrix and takes place either in a closed (dough) or open (crumb) structure. The existence of a moving evaporation front inside bread, which is a determining step of baking, is incorporated in a model applying a moving boundary formulation with equivalent thermophysical properties. The approach proposed here can be extended to other similar processes such as baking of other products (e.g. biscuit, cake), high-temperature drying, cooking and roasting.

Keywords: Simultaneous heat and mass transfer; Phase change; Stefan problem

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Nomenclature

a_w	Water activity
$\tilde{C}$	Equivalent heat capacity, J m^{-3} K^{-1}
C	Heat capacity, J m^{-3} K^{-1}
C_p	Specific heat, J kg^{-1} K^{-1}
D	Water (liquid or vapour) diffusion coefficient, m^{2} s^{-1}
H	Enthalpy, J m^{-3}
h	Heat transfer coefficient, Wm^{-2} K^{-1}
k	Thermal conductivity, W m^{-1} K^{-1}
k_g	Mass transfer coefficient, kg Pa^{-1} m^{-2} s^{-1}
P	Water vapour pressure, Pa
RH	Relative humidity, %
S	Interface position, m
T	Temperature, K
t	Time, s
W	Water (liquid or vapour) content, kg kg^{-1}

Greek symbols

δ	Delta function
ε	Emissivity
λ	Heat of phase change, J m^{-3}
ρ	Density, kg m^{-3}
σ	Stefan-Boltzmann constant, 5.67 10^{-8} W m^{-2} K^{-4}

Subscripts

∞	Ambient
f	Phase change
s	Solid or surface
sat	Saturated

1. Introduction

Baking of bread (and bakery products in general) can be defined as the process which transforms a dough basically made of flour, water and leavening agents in a high quality product with unique sensorial features. In particular, French or white bread is the most popular type of bread, and is distinguished for having a crunchy and brown crust, a sponge and light crumb with soft texture and intermediate moisture, and a typical flavour. All these quality aspects are result of a series of physical, chemical and biochemical changes occurring during baking, i.e. formation of a porous and open structure, volume expansion, water evaporation, starch gelatinization, protein denaturation, carbon dioxide production (leavening agents), crust formation, and development of browning (Maillard reaction and caramelization).

From a transport phenomena point of view, bread baking has been considered as a simultaneous heat and mass transfer (SHMT) problem in a porous medium. So far, some efforts have been made to well understand and therefore predict and control the bread baking process, including both experimental and theoretical approaches. Sluimer and Krist-Spit (1987) found that the temperature increase in a gas-free dough piece proceeds much slower than in a fermented dough, showing that heat conduction is of minor importance in dough baking. So, they suggested the principle of Watt or evaporation-condensation as the major mechanism of heat transport in baking. The theory of evaporation and condensation was proposed by Henry in 1939 (cited by de Vries et al., 1989); this process can be divided into four steps:

1. Water evaporates at the warmer side of gas cells, absorbing latent heat of vaporization.
2. Vapour migrates through the gas phase.
3. Vapour condenses at the colder side of the gas cell, setting free its latent heat.
4. Heat and water are transported by conduction and diffusion, respectively, through a dough membrane to the warmer side of the next gas cell, where the series of processes can start all over again.

When dough is transformed into crumb, the gas phase becomes continuous and the last step is not necessary. Evaporation-condensation will continue until the temperature of the whole crumb has achieved 100 ºC (Sluimer and Krist-Spit, 1987).

Since evaporation-condensation produces a water vapour transport towards the thermal core of the bread, it would be possible that the local moisture content increases during baking. By using a fibre optic instrument, Thorvaldsson and Skjöldebrand (1998) measured an increase in the water content of bread core after temperature had reached 70 ± 5 ºC, and suggested that the water is not free to move until the pore structure is opened up and becomes continuous. However, the fibre optic method is sensitive to the structure and temperature of the sample, and has to be improved (Wagner et al., 2007). On the other hand, Wagner et al. (2007) found an increase in moisture content at the core during the first minutes of baking when temperature did not exceed 65 ºC, tending to confirm the possible occurrence of the evaporation-condensation mechanism even in a closed porous structure (i.e. dough).

Zanoni et al. (1993) reported a phenomenological model where the variation in temperature and water content of bread during baking is determined by the formation of an evaporation front at 100 ºC. The progressive advancing of this evaporation front towards the inside of the product results in the formation of two separate regions: the crust, where moisture is very low and temperature asymptotically tends to the oven temperature; and the crumb, where moisture is constant and temperature asymptotically tends to 100 ºC (Zanoni et al., 1994). In this way, only external zones of bread suffers dehydration during baking; the development of the crust avoids the diffusion of internal water vapour in the bread to the outside (Hasatani et al., 1991; Wählby and Skjöldebrand, 2002). A similar interpretation of cake baking was given by Lostie et al., who divided the process in two periods, namely the "heating up" period and "crust and crumb" period, delimited by the formation of a dry crust at the batter heated surface (Lostie et al., 2002a, 2002b, 2004).

Another suggested hypothesis for bread baking is based on the mathematical model proposed by Luikov (1975) to describe SHMT during drying (Zheleva and Kambourova, 2005). This phenomenological approach applies the concept of irreversible thermodynamics and includes the effect of temperature on the water transport (i.e. *thermodiffusion*). Conversely, Zhang and Datta (2006) proposed a mechanistic basis to describe the bread baking process, involving dough deformation and multiphase heat and mass transfer. Further information about the state of the art is available elsewhere (Mondal and Datta, 2008; Sablani et al., 1998).

Thus far, many hypotheses have been proposed to explain the mechanisms of heat and mass transfer occurring in bread during baking. However, numerical results obtained from mathematical models based on the suggested theories are still not in well agreement with reported experimental findings (see further discussion in concomitant paper). As a part of a comprehensive research on bread baking (Purlis, 2007), the objective of this first article was to develop a mathematical model to correctly describe the water content and temperature variation in bread during baking. For this aim, various hypotheses were evaluated and discussed through the use of experimental data. Discussion about thermophysical properties of bread, solution and validation of the model and numerical simulation of the baking process are presented in the second part of this article (Purlis and Salvadori, 2008).

2. Materials and methods

2.1. Bread samples

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 by mixing the ingredients for 10 min in a home multi-function food processor at constant speed. Then individual samples of 100-150 g (cylindrical shape, ca. 0.15 m length, 0.04 m diameter) were formed and placed in a perforated tray. After 1.5 h proving at ambient temperature, samples duplicated their volume.

2.2. Baking tests

Dough samples were baked in an electrical static oven (Ariston FM87-FC, Italy) under two different baking conditions, depending on air velocity: natural convection (*v*

= 0 m/s) and forced convection (v = 0.9 m/s). Experiments were carried out by using three oven temperatures: 180, 200 and 220 ºC. The perforated tray with the samples was placed in the central zone of the oven in order to achieve a homogeneous distribution of heat and mass fluxes. Baking tests were divided into three groups according to the variable(s) being registered: temperature, water content and crust thickness, and weight loss of bread; this was necessary since experimental protocol was different for each measurement.

2.3. Temperature measurement

Temperature inside bread samples and in oven ambient was measured using T-type thermocouples (Omega, USA) connected to a data logger (Keithley DASTC, USA) which was incorporated to a PC; sampling time was set to 5 sec in all cases. It is worth to note that thermocouples had to be inserted in the product before the proving stage because dough easily collapses if any pressure is done over the surface just before baking, since is a porous liquid matrix at that moment. Moreover, the proving step was carried out inside the oven (turn off) to allow any movement of thermocouples while introducing the tray inside the chamber. Thermocouples were placed in different positions of dough between the centre and the surface along the axial axis; final locations of thermocouples were determined after baking. Each baking condition was done by duplicated using four bread samples each time.

2.4. Water content, crust thickness and weight loss measurement

Water content was measured in five different regions along the vertical axis of the central cross-section (1 cm thickness) of bread samples: lower, central and upper crumb, and lower and upper crust (Figure 1). Sampling was performed every 10 min for 180 and 200 ºC, and every 7 min for 220 ºC baking temperature. Also, moisture content of unbaked dough was determined. Water content values were calculated by drying the samples in a vacuum oven (Gallenkamp, United Kingdom) at 80 ºC, until constant weight was achieved. Crust thickness was determined using a calliper in the same experiments as water content. Several measures of each sample were recorded and then an average value was obtained for each baking time.

Weight loss during baking was assessed by weighing the tray with samples (outside the oven) every 5 min. It is worth to note that this procedure took about 5 sec each time, thus it was assumed that no significant perturbation was introduced in measurement. All tests were done by duplicate with the oven under steady regime condition.

3. Experimental results

3.1. Temperature

Temperature variation at different regions of bread during baking is shown in Figure 2; only one baking condition is illustrated for simplicity though all experimental runs presented a similar behaviour. Firstly, it can be seen the set-up profile followed by the oven air temperature during the initial phase of baking, certainly due to the experimental protocol established in subsection 2.3. Once the set value for air temperature is achieved the oven controls this parameter with ±3.3 ºC accuracy showing an oscillating tendency. Temperature at bread surface (0 cm position) described a similar variation as air temperature, increasing almost constantly until 120 ºC was reached and then following the oven temperature behaviour.

On the other hand, in the core zone of bread (at 2 cm from surface) the temperature slightly increased during the first 10 minutes since thermal gradient had not been established yet, but then a rapid temperature raise was observed achieving a maximum heating rate of 11.6 ºC/min at 16 minutes baking. Since 20 minutes, the core temperature stopped increasing and described a plateau at 98 ºC until the end of baking. Notice from Figure 2 the sigmoid shape of temperature variation at the centre of bread, which is very similar to the ones obtained during heating of multi-dimensional moistened objects (Sommier et al., 2005). In the intermediate zone (0.5 and 0.6 cm positions), i.e. underneath the surface but not at the core of bread, the temperature variation showed hybrid behaviour between previous descriptions. Initially, temperature increased in a similar way as surface but when values about 98-100 ºC were attained, it remained constant in a plateau towards the end of baking. It is worth to note that temperature at the closer position to surface (0.5 cm) left the plateau from 25 minutes and started to increase again above 100 ºC.

3.2. Water content, crust thickness and weight loss

Figure 3 presents typical variation of water content in bread during baking, where two different situations can be well distinguished. From one side, outer zones of bread suffered dehydration during all the process, which actually leads to the formation of a crust. At the end of baking, values for water content of crust were in the range 5-10% (wet basis), depending on process condition, i.e. high oven temperature and forced convection produced more dehydration. On the other hand, the crumb zone beneath the crust maintained the moisture content of the unbaked dough throughout the baking process. Furthermore, at the core region (central crumb) we detected an increase between 0.4 and 2.3% in the water content respect to initial condition, in all baking experiments, i.e. the bread core increased its moisture during all the process. Bearing in mind that we used the same method for water content measurement as Wagner et al. (2007), our findings complement their results obtained at the very beginning of baking, confirming the occurrence of the evaporation-condensation mechanism during all the process. This implies that evaporation-condensation is not determined by the state of the porous structure (i.e. open or closed), but is a characteristic mechanism given in high moisture porous media.

Weight or average moisture content of bread continuously decreased during baking, which is in agreement with the variation in water content at the crust (Figure 4). However, the drying rate was not constant as can be seen from Figure 5. Hasatani et al. (1991) did not observe a constant drying rate period either, and they found that the bread crust was generated from the time when the drying rate achieved the maximum peak and the temperature stopped increasing at 100 ºC. So, the drying rate increases up to a crust is formed, but then it begins to decrease due to the enlarging of crust thickness (Figure 6). In this way, the crust avoids further dehydration of bread, acting as barrier to mass transfer towards the oven ambient (Wählby and Skjöldebrand, 2002).

4. Mathematical model

Beyond the several complex changes occurring in bread during baking, the most characteristic aspects are the rapid heating of bread core and development of a crust.

Sluimer and Krist-Spit (1987) proposed the evaporation-condensation mechanism to explain the former, suggesting that heat conduction is of minor importance in dough baking. Certainly, the experimental findings reported in this work together with the ones published by Wagner et al. (2007) confirm the occurrence of evaporation-condensation in the dough/crumb of bread during baking. Secondly, the formation and advancing of an evaporation front towards the core are responsible for the development of a crust which restricts the water vapour diffusion to the outside of bread. Note that bread baking must be considered as a SHMT problem in a porous medium.

Thus, bread can be modelled as a system containing three different regions:

1. Crumb: wet inner zone, where temperature does not exceed 100 ºC and dehydration does not occur.
2. Crust: dry outer zone, where temperature increases above 100 ºC and dehydration takes place.
3. Evaporation front: between the crumb and crust, where temperature is ca. 100 ºC and water evaporates.

The evaporation front is actually a moving interface where a phase change happens. The same situation is observed in processes which involve melting and freezing (i.e. solid-liquid phase change), such as metal casting, manufacturing of ice, thermal storage and thawing and freezing of food; and processes with liquid-vapour (evaporation) or solid-vapour phase change (sublimation) such as frying, high temperature drying, spray- and freeze-drying of food and non-food materials (Farid, 2002). All these processes are catalogued as moving boundary problems (MBP), though the second group is more complicated by the vapour diffusion throughout the dried zone of the material (Farid, 2002). Therefore, we consider bread baking as a MBP as well.

Mathematically, a MBP (often called as Stefan problem) is related to time-dependent problems (i.e. parabolic type equations) where boundary position must be determined as function of time and space (Crank, 1987). For instance, let us consider the melting of some material; this type of problem can be formulated considering the heat balance equation for each region i.e. solid and liquid regions (not shown for simplicity), and establishing the following interface condition besides temperature continuity condition:

$$k_2(T)\frac{\partial T_2}{\partial x} - k_1(T)\frac{\partial T_1}{\partial x} = \lambda \frac{\partial S}{\partial t} \tag{1}$$

where subscripts 1 and 2 symbolize solid and liquid regions, respectively. This boundary condition represents the *enthalpy jump* at the temperature of phase transition. Based on a physical approach, a different mathematical formulation is possible by defining an *equivalent* heat capacity per volume unit through the enthalpy definition (Bonacina et al., 1973):

$$\tilde{C}(T) = \frac{dH(T)}{dT} = C(T) + \lambda\delta(T - T_f), \quad C(T) = \begin{cases} C_1(T), & T < T_f \\ C_2(T), & T > T_f \end{cases} \tag{2}$$

Applying this approach to thermal conductivity, the two-region problem including an interface condition can be solved by only one partial differential equation with equivalent coefficients that include the phase change. For a generalized and unique solution to the problem, smoothed heat capacity and thermal conductivity must be defined: a Delta-type function is used instead of Delta function in order to achieve large but finite values in the phase transition temperature range (Bonacina et al., 1973).

So, the mathematical model for bread baking presented in this work is based on the MBP formulation described above. Note that no empirical coefficient to determine the interface position or any imposed additional condition is needed for including the formation and advancing of the evaporation front inside bread in the model. Furthermore, the following assumptions were used to develop the mathematical for bread baking:

- Control volume is homogeneous and continuous; the porous medium concept is included through effective or apparent thermophysical properties.
- Volume change during baking is neglected (this phenomenon is under study and will be incorporated in the model in a future work).
- There exists local thermodynamic equilibrium.
- Heat is transported by conduction from surface to bread core according to Fourier's law, but an effective thermal conductivity is used to incorporate the evaporation-condensation mechanism in heat transfer.
- Energy from oven ambient to bread surface is transferred by convection and radiation.
- Only liquid diffusion in the crumb and only vapour diffusion in the crust are assumed to occur (Luikov, 1975).
- Liquid water migrates from the core towards to the evaporation front under a water content gradient, and liquid water flux is described by Fick's diffusion law.
- Water evaporates at 100 ºC.
- Water vapour migrates from the evaporation front to bread surface under a water vapour concentration gradient, and mass flux is described by Fick's diffusion law.
- Water vapour is transferred to oven ambient through convective flux.
- A smoothed Heaviside function replaces the Delta function for defining equivalent thermophysical properties in the MBP formulation.

The evaporation-condensation mechanism is incorporated in the model, but only in the heat transfer balance; we neglect its contribution to mass transport since the water content increase at the bread core is not relevant opposite to overall weight loss during baking. In addition, more information is needed to include this mechanism in the mass balance due to its complexity. Following, the heat and mass balance equations and boundary conditions of the SHMT model are presented.

4.1. Governing equations

Heat balance equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T \right) \tag{3}$$

Mass balance equation:

$$\frac{\partial W}{\partial t} = \nabla \cdot \left(D \nabla W \right) \tag{4}$$

All thermophysical properties are continuous functions including the phase change, and are valid for the entire temperature and water content ranges observed during baking, i.e. both balances consider SHMT in dough, crumb and crust. Description and analysis of thermophysical properties are presented in the second article (Purlis and Salvadori, 2008).

4.2. Boundary conditions

The heat arriving to the bread surface by convection and radiation is balanced by conduction inside the bread:

$$-k\nabla T = h(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_\infty^4) \tag{5}$$

The water migrating towards the bread surface is balanced by convective flux:

$$-D\rho_s \nabla W = k_g\left(P_s(T_s) - P_\infty(T_\infty)\right) \tag{6}$$

where $P_s = a_w\, P_{sat}(T_s)$ and $P_\infty = RH\, P_{sat}(T_\infty)$.

Further discussion about boundary conditions is included in the second paper (Purlis and Salvadori, 2008).

5. Conclusions

The evaporation-condensation mechanism proposed to explain the rapid heating of porous dough during baking is confirmed through experimental findings. Evaporation-condensation appears as a characteristic mechanism of porous media, and occurs either if the porous structure is closed (dough) or open (crumb) until the temperature has reached 100 ºC (i.e. evaporation temperature). Furthermore, the existence of a progressive evaporation front is essential for the bread baking process; the advancing of this interface produces the outer crust which avoids dehydration of the crumb due to structural characteristics that restricts the water vapour diffusion from the bread core to the oven ambient.

These two major phenomena are incorporated in a mathematical model to describe the simultaneous heat and mass transfer occurring during baking of bread. Though bread baking is clearly a moving boundary problem, it is the first time that a rigorous MBP formulation is applied to model this process. This approach gives the possibility of handling simple equations with continuous equivalent (and apparent) thermophysical properties, valid for the entire operative range of baking. Besides, no empirical parameters or imposed or fictitious boundary conditions are used to determine the interface position, i.e. the model describes the evaporation front in a natural, unforced way.

Finally, the mathematical model presented in this work can be used to study the baking of other products, such as biscuit, cake and other types of bread. As well, this formulation could be implemented for modelling other processes with simultaneous heat and mass transfer and a moving phase change interface, e.g. high-temperature drying, cooking, roasting.

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References

Bonacina, C., Comini, G., Fasano, A., & Primicerio, M. (1973). Numerical solution of phase-change problems. *International Journal of Heat and Mass Transfer*, 16, 1825-1832.

Crank, J. (1987). *Free and moving boundary problems*. Oxford University Press, UK.

de Vries, U., Sluimer, P., & Bloksma, A.H. (1989). A quantitative model for heat transport in dough and crumb during baking. In *Cereal Science and Technology in Sweden*, N. G. Asp (Ed.). Sweden, 174-188.

Farid, M. (2002). The moving boundary problems from melting and freezing to drying and frying of food. *Chemical Engineering and Processing*, 41, 1-10.

Hasatani, M., Arai, N., Katsuyama, H., Harui, H., Itaya, Y., Fushida, N., & Tatsukawa, N. (1991). Heat and mass transfer in bread during baking in an electric oven. In *Drying 91*, A. S. Mujumdar & I. Filkova (Eds.). Amsterdam, 385-393.

Lostie, M., Peczalski, R., & Andrieu, J. (2004). Lumped model for sponge cake baking during the "crust and crumb" period. *Journal of Food Engineering*, 65, 281-286.

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

Lostie, M., Peczalski, R., Andrieu, J., & Laurent, M. (2002b). Study of sponge cake batter baking process. II. Modeling and parameter estimation. *Journal of Food Engineering*, 55, 349-357.

Luikov, A.V. (1975). Systems of differential equations of heat and mass transfer in capillary-porous bodies (review). *International Journal of Heat and Mass Transfer*, 18, 1-14.

Mondal, A., & Datta, A.K. (2008). Bread baking- a review. *Journal of Food Engineering*, 86, 465-474.

Purlis, E. (2007). *Simulación de las transferencias simultáneas de materia y energía en el proceso de horneado de pan mediante elementos finitos*. PhD thesis, Universidad Nacional de Quilmes, Argentina.

Purlis, E., & Salvadori, V.O. (2008). Bread baking as a moving boundary problem. Part 2: Model validation and numerical simulation. *Journal of Food Engineering*, submitted for publication.

Sablani, S.S., Marcotte, M., Baik, O.D., & Castaigne, F. (1998). Modeling of simultaneous heat and water transport in the baking process. *Lebensmittel-Wissenschaft und-Technologie*, 31, 201-209.

Sluimer, P., & Krist-Spit, C.E. (1987). Heat transport in dough during the baking of bread. In *Cereals in a European Context*, I. D. Morton (Ed.). UK, 355-363.

Sommier, A., Chiron, H., Colonna, P., Della Valle, G., & Rouillé, J. (2005). An instrumented pilot scale oven for the study of French bread baking. *Journal of Food Engineering*, 69, 97-106.

Thorvaldsson, K., & Skjöldebrand, C. (1998). Water diffusion in bread during baking. *Lebensmittel-Wissenschaft und-Technologie*, 31, 658-663.

Wagner, M.J., Lucas, T., Le Ray, D., & Trystram, G. (2007). Water transport in bread during baking. *Journal of Food Engineering*, 78, 1167-1173.

Wählby, U., & Skjöldebrand, C. (2002). Reheating characteristics of crust formed on buns, and crust formation. *Journal of Food Engineering*, 53, 177-184.

Zanoni, B., Peri, C., & Pierucci, S. (1993). A study of the bread-baking process. I: A phenomenological model. *Journal of Food Engineering*, 19, 389-398.

Zanoni, B., Pierucci, S., & Peri, C. (1994). Study of the bread baking process – II. Mathematical modelling. *Journal of Food Engineering*, 23, 321-336.

Zhang, J., & Datta, A.K. (2006). Mathematical modeling of bread baking process. *Journal of Food Engineering*, 75, 78-89.

Zheleva, I., & Kambourova, V. (2005). Identification of heat and mass transfer processes in bread during baking. *Thermal Science*, 9, 73-86.

Figure captions

Figure 1. Sampling regions for determination of water content distribution in bread during baking. The schema represents the central cross-section (1 cm thickness) in the axial direction of bread.

Figure 2. Temperature variation in bread during baking at 180 ºC under natural convection condition. Final locations of thermocouples are given in terms of distance from upper surface along the vertical axis of the middle cross-section of bread. Final height of bread: 5 cm.

Figure 3. Water content (wet basis) variation in bread during baking at 180 ºC under natural convection condition. Initial (i.e. unbaked dough) moisture corresponded to 39.71%.

Figure 4. Weight loss (relative to initial dough mass) of bread as a function of baking time. (◇) 180 ºC; (□) 200 ºC; (△) 220 ºC. Filled symbols for natural convection and empty symbols for forced convection.

Figure 5. Drying rate of bread as a function of baking time. (◇) 180 ºC; (□) 200 ºC; (△) 220 ºC. Filled symbols for natural convection and empty symbols for forced convection.

Figure 6. Variation of crust thickness during baking. (◇) 180 ºC; (□) 200 ºC; (△) 220 ºC. Filled symbols for natural convection and empty symbols for forced convection.

Fig.1

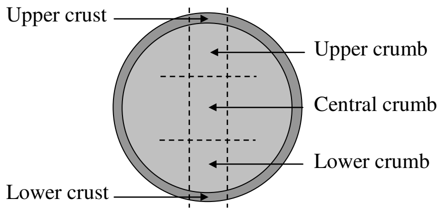

Upper crust
Upper crumb
Central crumb
Lower crumb
Lower crust

Figure 2

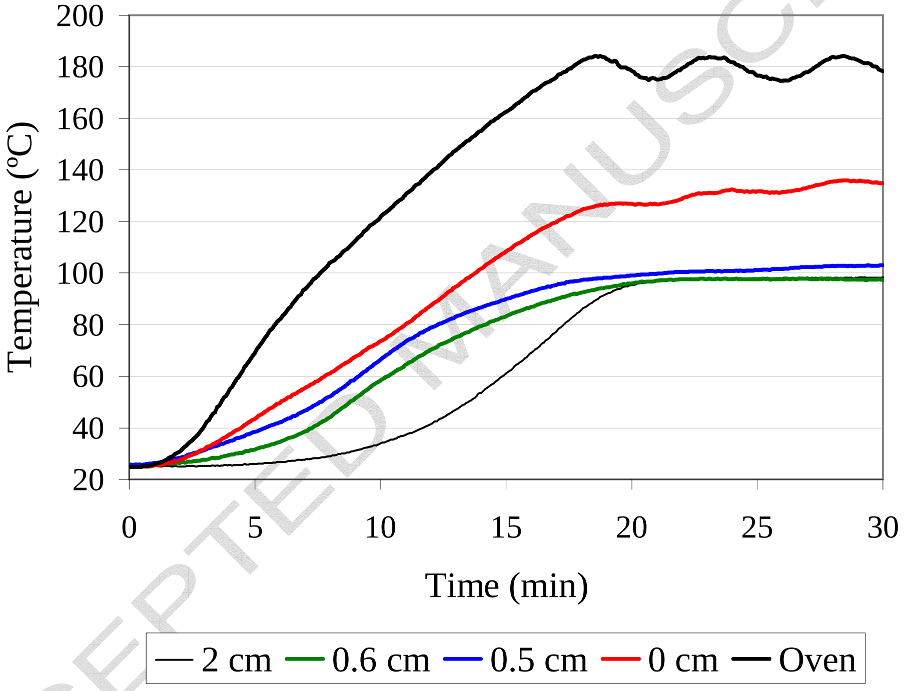
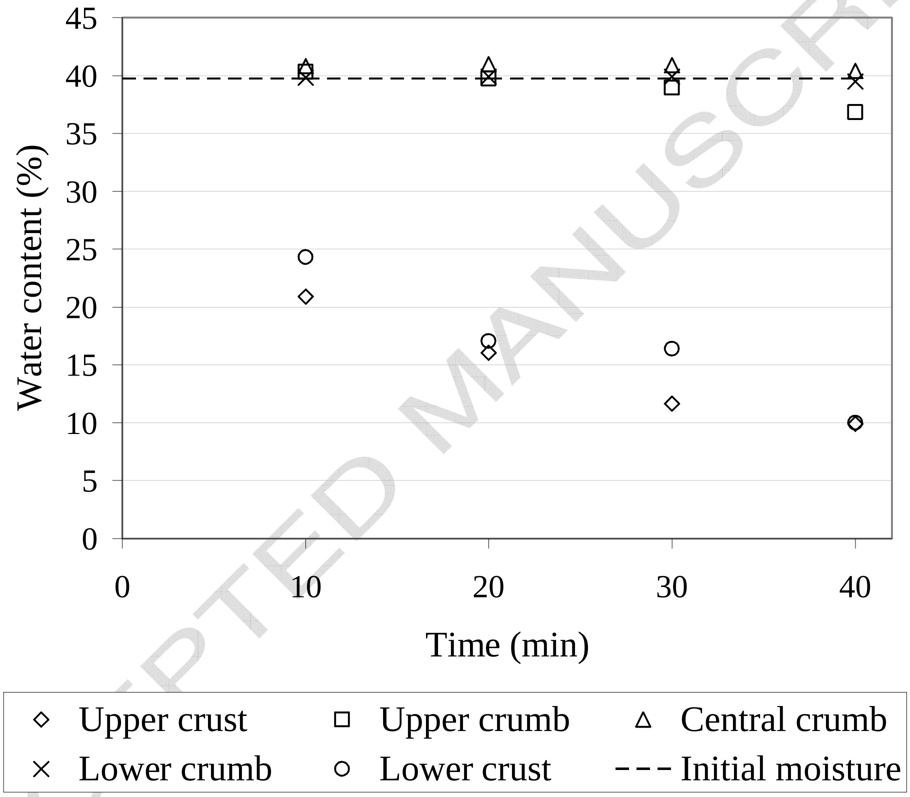

200
180
160
140
120
100
80
60
40
20
Temperature (ºC)
0
5
10
15
20
25
30
Time (min)
2 cm
0.6 cm
0.5 cm
0 cm
Oven

Figure 3


45
40
35
30
25
20
15
10
5
0
Water content (%)
0
10
20
30
40
Time (min)
◇ Upper crust
□ Upper crumb
△ Central crumb
× Lower crumb
○ Lower crust
--- Initial moisture

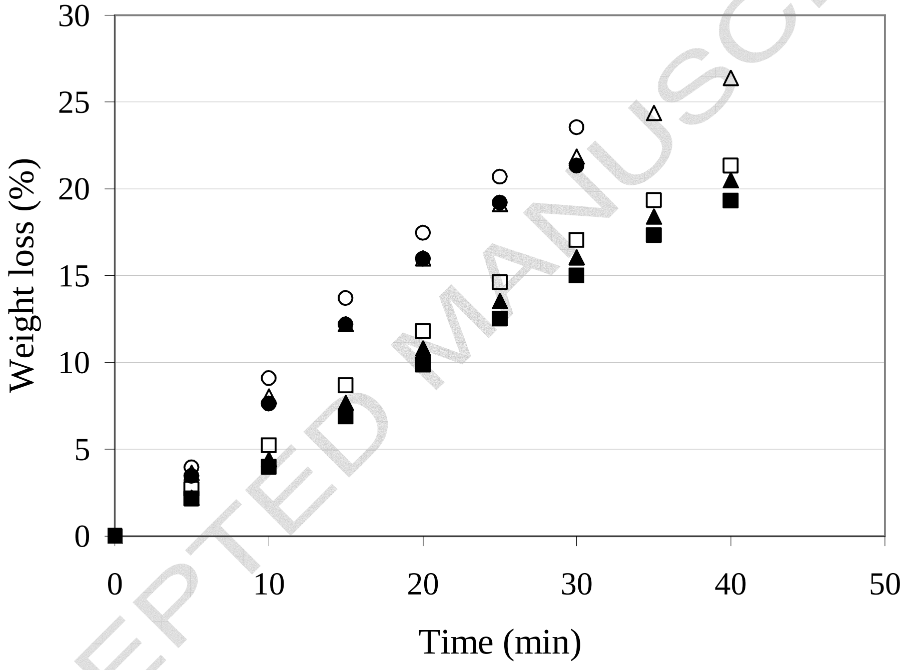

Weight loss (%)
0
5
10
15
20
25
30
Time (min)
0
10
20
30
40
50

Figure 5

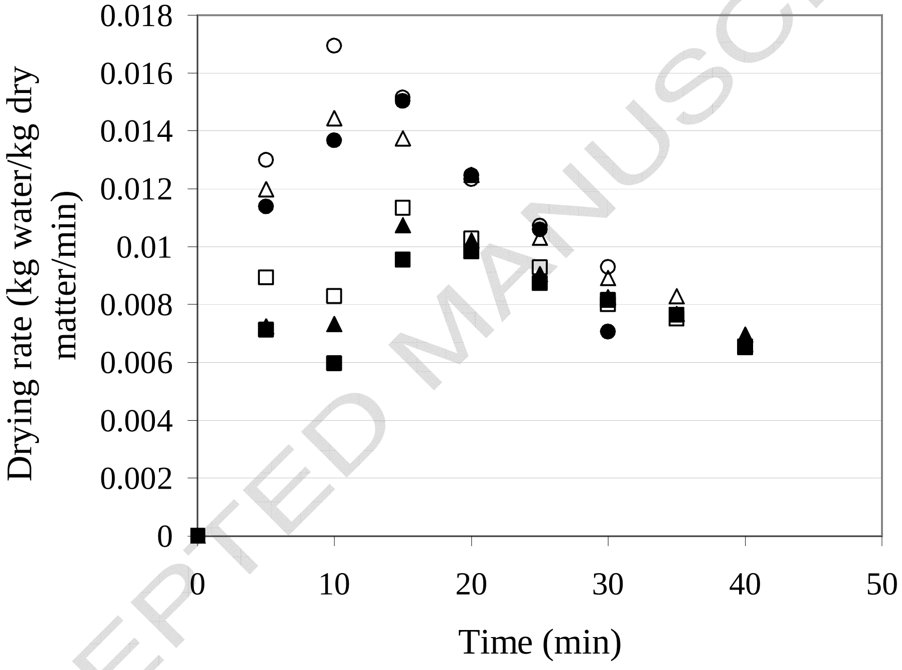

0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Drying rate (kg water/kg dry matter/min)
0
10
20
30
40
50
Time (min)

Figure 6