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Research Paper

Drying of coating on bun bread: Heat and mass transfer numerical model

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The application of edible coating in bakery products could be a suitable alternative to maintain safety, textural and organoleptic characteristics during the storage. To achieve a continuous coating layer, the coating solvent should be eliminated by a drying process, avoiding the food internal dehydration. The main factors that influence the drying time of the coating are the temperature, thickness of the coating and the solvent concentration. In order to define the optimal drying time, numerical modelling could provide a suitable alternative to experimental techniques. In this study, finite elements models able to describe the heat and moisture transfer inside and on the surface of coated bun breads, as function of drying temperature, time and coating thickness were developed and validated. A good agreement was obtained between calculated and experimental data reporting RMSE of 0.04 and 0.05 $kg_{water}\ kg_{solid}^{-1}$ for the samples dried at 25 and 60 °C, respectively. A relation between the optimal drying time, coating thickness and the drying temperature was determined ($R^2 = 0.981$, 95% confidence bounds). The model could be used for other coating formulations and bakery products, simply by changing material properties and geometrical dimensions.

1. Introduction

Staling and mold spoilage are the main factors that restrict the quality of bread. The stability during storage can be defined as the maintenance of the microbiological, physical and sensorial attributes related to freshness, such as tenderness, compressibility and humidity (Paeschke, 1997). Shelf-life of bread without any preservatives is generally about 3–4 days (Muizniece Brasava et al., 2012; Noshirvani, Ghanbarzadeh, Mokarram, & Hashemi, 2017). Due to water activity of around 0.96 bread is susceptible to mold growth (Cioban, Alexa, Sumalan, & Merce, 2010). The fungal proliferation determines the shelf-life of bread and bakery products. Along with mold contamination, staling is another

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important attribute for the bakery product quality (Bartolozzo, Borneo, & Aguirre, 2016). Staling is defined as a term which indicates decreasing consumer acceptance of bakery products caused by changes in crumb and crust other than those resulting from the action of spoilage organisms (Bechtel, Meisner, & Bradley, 1953). Particularly, staling includes complex processes that induce changes in mouth-feel, texture, loss of tenderness, humidity redistribution and partial dryness (Bartolozzo et al., 2016).

Coating and edible films have been taken into consideration in food preservation due to their ability to improve global food quality and increase the shelf-life (Chillo et al., 2008). These substances have been used to improve mechanical properties, the gas and moisture barriers, sensory perceptions, convenience, microbial protection (Galus & Kadzinska, 2015). In this way, the application of edible coating or films in bread products could be a suitable alternative to maintain safety, textural and organoleptic characteristics during the storage (Ferreira Saraiva et al., 2016).

An edible film or coating has been defined as thin layered structure of biopolymer that can be consumed and is usually applied onto a product surface in a liquid form by brushing, dipping or spraying (Bourtoom, 2008; Soukoulis et al., 2014). One or more fluid layers can be deposited and subsequently dried to form solid films. To set up a suitable coating procedure, food product parameters such as composition, shape, dimension and density, processing factors (temperature, static/dynamic, time), and coating formulation (solvent, viscosity, composition) have to be taken into account (Embuscado & Huber, 2009). To achieve a continuous layer, the solvent can be eliminated by drying at ambient or controlled conditions (Galus & Kadzinska, 2015). Various factors are relevant in the drying of coating: the temperature at which the process is performed, the thickness of the coating and the solvent concentration (Blandin, David, & Vergnaud, 1987). The time and the method of drying can significantly affect the physical properties of the final film (Soazo, Rubiolo, & Verdini, 2011; Pérez-Gago & Krochta, 2002). To optimise the drying of coating, it is essential to study the relation between temperatures, time and type fluid dynamics or flow conditions (e.g natural or forced convection). The optimal drying time can be seen as the time necessary to completely remove the solvent from the product surface, avoiding the food internal dehydration. Regarding the research works on the application of the coating on bakery products, the drying time of the edible films appears to have been empirically selected and a justification was not reported. Low temperature drying at 60 °C for 10 min in an air circulating drying chamber, and high temperature-short time drying (180 °C for 2 min) have been used by Soukoulis et al. (2014) to dry a probiotic edible coating Q3 on the crust of the bread. Ferreira Saraiva et al. (2016) reported a temperature of 180 °C for 5 min to dry coated panettones with an edible film of active potato starch. Lower temperatures for longer time (40 °C for 40 min, 60 °C for 2 h and 1 h at ambient temperature under forced ventilation) have been used on coated muffin, commercial crackers and bread, respectively by Bartolozzo et al. (2016), Bravin, Peressini, and Sensidoni (2006) and Noshirvani et al. (2017).

In order to define the optimal drying time, numerical modelling could provide a suitable alternative to experimental techniques (Defraeye, 2014). In experiments, some biological and experimental variability will be inherently present, which makes extensive parametric studies challenging. A particular advantage is that the properties of the thin film (e.g. thickness, solvent concentration, position on the product) can be exactly controlled, such as the shape and size of the coated product. Furthermore, the modelling provides high spatial and temporal resolution on moisture transport predictions (Defraeye & Verboven, 2017). The aim of this study was to develop and validate a finite elements model able to describe the drying of an edible coating on a bun bread, varying several process conditions (temperature, time and heating properties), coating properties (moisture content, thickness, position) and product characteristics. The model was used to determine the optimal coating drying time, avoiding the food internal dehydration.

2. Materials and methods

2.1. Model development

The main physical phenomena that should be considered in the process of drying are the diffusion of the solvent (water) through the solid ingredients of coating and then the evaporation. To study the drying time of coating on the bread surface, a 1D finite element model was developed by using Comsol Multiphysics (Comsol, Inc., Burlington, MA). A 2D axisymmetric model based on the geometry reported in Fig. 1, was exclusively developed to evaluate the influence of the surface temperature distribution on the mass flux. Indeed the surface temperature depends on the shape of the sample and so it is important to evaluate the effect of the temperature distribution on the mass flux. If this effect is negligible, the simpler 1D model could be used.

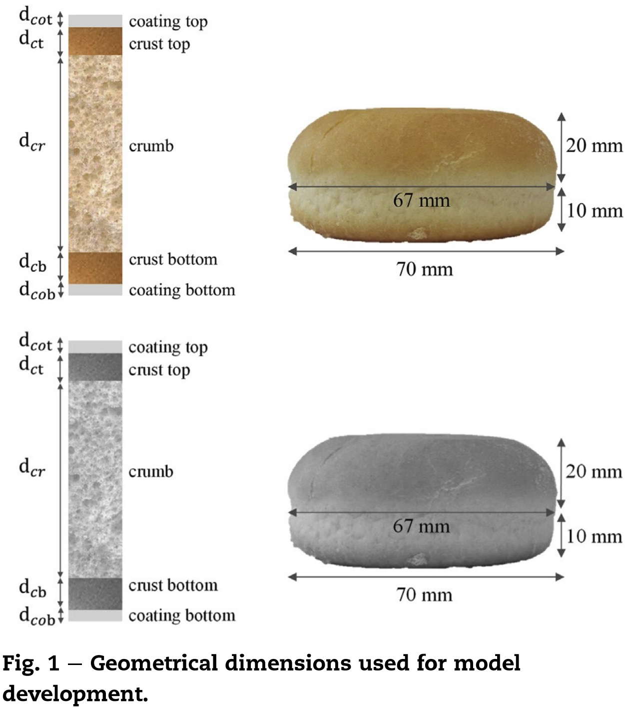

Fig. 1 – Geometrical dimensions used for model development.

The dimension values are the average of the measurement carried out on ten breads. Both the models describe the heat and moisture transfer inside and on the surface of coated breads. The main model assumptions are that the shrinkage of the coating was not considered, that the evaporation occurs only at the air-coating interface, and that the initial moisture concentrations are uniform. The model geometry was composed by 5 different zones, as reported in Fig. 1, parametrically defined by the distance from the edge. Each zone is characterised by its own physical properties.

The mesh of the 1D model was characterised by edge elements symmetrically distributed in relation to the geometrical centre, with a ratio between bigger and smaller elements being 500. For the 2D model, an unstructured mesh with triangular elements was generated. Furthermore, 6 layers of quadrilateral boundary elements characterised by a stretching factor of 1.2 (increase in thickness between two consecutive boundary layers) has been applied on all boundaries. For both models the mesh was refined up to a level for which the calculus improvements were not significant.

2.1.1. Governing equations

2.1.1.1. Mass transfer. The moisture transfer inside the product was governed by the following mass transfer equation conformal to the second Fick's law:

$$\frac{\partial C}{\partial t} = \nabla\cdot(D\nabla C) \tag{1}$$

where C (mol m^{-3}) is the calculated moisture concentration at time t (s), D (m^2 s^{-1}) is the water diffusion coefficient through the involved material. The diffusion coefficient of crust and crumb were set on the basis of the values found in literature (Monteau, 2008; Purlis, 2011). The coating diffusion coefficient ($D_{coating}$) was experimentally determined combining drying experimental data and inverse numerical method (Zogzas, Maroulis, & Marinos-Kouris, 1994, Fabbri, Cevoli, and Troncoso (2014)). A relation between diffusion coefficient, moisture concentration and temperature was determined (Blandin et al., 1987):

$$D_{coating} = a\exp\left(-\frac{b}{T}\right)\exp\left(-\frac{d}{C}\right) \tag{2}$$

where T (K) is the calculated temperature at time t(s) and a, b and d are the equation parameters. The drying experimental curves were obtained by using a thermobalance (i-Thermo 163M, Exacta-Optech, Italy) following the procedure proposed by Arranz, jimenez-Ariza, Diezma, and Correa (2017). Three mm of coating (the same formulation used for the model validation) was applied on to an aluminium plate (diameter of 10 cm) and then exposed to drying at different temperatures (25, 40, 60 and 80 °C). The sample weight was automatically recorded. A simple numerical model replacing the experimental geometry dimensions and drying conditions was developed. By the inversion of the numerical model, the computed mean moisture content values were compared to the experimental ones and the parameters of the diffusion coefficient equation were estimated as shown in Table 1. The optimization procedure was the same as proposed by Fabbri et al., 2014. All the values of the material properties are given in Table 1.

2.1.1.2. Heat transfer. Inside the product heat is transferred by conduction and is described by the following partial differential equation:

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

where: C_P (J K^{-1}kg^{-1}), k (W m^{-1}K^{-1}) and ρ (kg m^{-3}) are the specific heat, thermal conductivity and density of the different parts of the product (coating, crust and crumb), respectively. Thermal conductivity and the thermal diffusivity (θ, m^2 s^{-1}) have been experimentally determined by using the needle probe KD2 (Decagon Device Inc., Pullman, USA) on the same type of bun bread used for the model validation. The density ρ (kg m^{-3}) was also experimentally determined (Zanoni, Pierrucci, & Peri, 1994). The specific heat (J K^{-1}kg^{-1}) was consequently calculated by the following equation:

$$C_P = \frac{k}{\rho\theta} \tag{4}$$

The values of material properties are given in Table 1.

2.1.2. Boundary conditions

Concerning the boundary conditions, flux conditions were imposed on the interface between the coated product surface and the air.

2.1.2.1. Mass flux.

$$n\cdot(-D\nabla C) = N = h_m\left(\frac{P_\infty}{RT_\infty} - \frac{P_s}{RT_s}\right) \tag{5}$$

where N (mol m^{-2}s^{-1}) is the water molar flux, R (J mol^{-1}K^{-1}) is the universal gas constant and h_m (m s^{-1}) is the mass transfer coefficient calculated on the basis of the well-known Chilton-Colburn analogy between the Nusselt number and the Sherwood number (Sh):

$$h_m = \frac{ShD_a}{L} \tag{6}$$

For the 1D model:

$$\text{top surface: } Sh_t = 0.54(Gr_m Sc)^{1/4}, \tag{7}$$

$$\text{bottom surface: } Sh_b = 0.27(Gr_m Sc)^{1/4}, \tag{8}$$

where:

$$Sc = \frac{\mu_a}{\rho_a D_a}: \text{ Schmidt numbers}, \tag{9}$$

$$Gr_m = \frac{gL^3\rho_a(\rho_s - \rho_\infty)}{{\mu_a}^2}: \text{ Grashof number for the mass flux}, \tag{10}$$

$$\rho_s = X_s\rho_a: \text{ density of humid air at the coated bread surface (kg m}^{-3}), \tag{11}$$

$$\rho_\infty = X_\infty\rho_a: \text{ density of humid air far from the coated bread surface (kg m}^{-3}), \tag{12}$$

Table 1 – Material properties and initial condition implemented in the model.

	Crumb	Crust top/bottom	Coating	Air
Material properties				
Thermal conductivity, k ($Wm^{-1}K^{-1}$)	0.31	0.21	0.52	$-2.28E-3+1.155E-4T-7.9E-8T^2+4.12E-11T^3-7.44E-15T^4$
Density, ρ (kgm^{-3})	310	200/230	950	346.52/T
Specific heat, C_P ($Jkg^{-1}K^{-1}$)	2600	2200	3900	$1.05E+3-3.73E-1T+9.45E-4T^2-6.02E-7T^3+1.28E-10T^4$
Diffusion coefficient, D (m^2s^{-1})	5.98E-11	1.00E-10	2.2E-14exp (0.0255T) exp (-444/C)	$-2.775E-6+4.479E-8T+1.656E-10T^2$
Dynamic viscosity, μ_a (Pas)	–	–	–	$-75.20E-10+4.427E-8T-7.887E-12T^2$
Initial conditions				
Moisture concentration, C ($molm^{-3}$, $kg_{water}\ kg_{solid}^{-1}$)	4900, 0.44	2600, 0.23 3100, 0.27	51,600, 13.26	–
Temperature, T (°C)	20	20	20	25°C–90 °C

where ρ_a (kg m^{-3}) and μ_a (Pa s) are the density and dynamic viscosity of the air, respectively (data reported in Table 1).

For the 2D axisymmetric model:

$$Sh = 0.59(Gr_m Sc)^{1/4} \tag{13}$$

The vapour pressure in the drying cabinet far from the product surface (P_∞), and the vapour pressure close to coating surface (P_s), are determined on the basis of the vapour relative humidity in the cabinet far from the product surface (RH_c) and the water activity at the interface (aw_s), together with the corresponding temperature, via saturated vapour pressure P_{sat} (T) given by Antoine's law:

$$P_{sat}(T) = \left[10^{\left(8.07131-\frac{1730.63}{233.426+T}\right)}\frac{10^5}{760}\right] \tag{14}$$

$$P_\infty = RH_c P_{sat}(T_\infty) \tag{15}$$

$$RH_c = \left(\frac{X_\infty P_{atm}}{0.622P_{sat}(T_\infty) + P_{sat}(T_\infty)X_\infty}\right) \tag{16}$$

$$X_\infty = 0.622\left(\frac{RH_{amb}P_{sat}(T_{amb})}{P_{atm} - RH_{amb}P_{sat}(T_{amb})}\right) : \text{ water content far from the surface } (kg_{water}kg_{solid}^{-1}) \tag{17}$$

If the RH_c value is known, the value could be directly inserted in the model.

$$P_s = aw_s P_{sat}(T_s) \tag{18}$$

$$aw_S = \frac{-B_1 - \sqrt{B_1{}^2 - 4B_0B_2}}{2B_2} : \text{ water activity of the coating} \tag{19}$$

Determined fitting the experimental drying data by the GAB model, where:

$$B_0 = \frac{1}{C_g K X_m} \tag{20}$$

$$B_1 = \frac{C_g - 2}{X_m C_g} - \frac{1}{X_S} \tag{21}$$

$$B_2 = \frac{K}{X_m}\frac{1}{C_g - 1} \tag{22}$$

$$X_s = \frac{CPM_{H2O}}{\rho_s} : \text{ water content at the surface} (kg_{water}kg_{solid}^{-1}) \tag{23}$$

PM_{H2O} is the water molecular weight (0.018 kg mol^{-1}) and ρ_S is the density of the dried coating (kg m^{-3}) as reported in Table 1, whereas the GAB model parameters are: X_m= 0.07, $K = 0.99$ and $C_g = 1.7$.

2.1.2.2. Heat flux.

$$n\cdot(-k\nabla T) = q = h(T_\infty - T) - N[C_{Pv}(T - T_{ref}) + L_v]PM_{H_2O} \tag{24}$$

where q (W m^{-2}) is the heat flux, T_∞ (K) is the drying cabinet temperature, h (W $m^{-2}K^{-1}$) is the convective heat transfer coefficient depending on the product geometry and the ambient flow conditions (natural or forced convection), C_{Pv} (1000 J $kg^{-1}K^{-1}$) is the specific heat of water vapour, L_v is the water latent heat (2256 kJ kg^{-1}) and T_{ref} is the reference temperature equal to 273.15 K.

For the natural convection in air, the convective heat transfer coefficient (h) can be obtained using the Nusselt number (Nu) by the following equation (Incropera, DeWitt, Bergman, & Lavine, 2006):

$$h = \frac{Nuk_a}{L} \tag{25}$$

Concerning the 1D model:

$$\text{For the top surface: } Nu_t = 0.27Ra^{1/4} \tag{26}$$

$$\text{while for the bottom surface: } Nu_b = 0.54Ra^{1/4} \tag{27}$$

$$Ra = GrPr : \text{ Rayleigh number} \tag{28}$$

$$Gr = \frac{g\beta L^3\rho_a^2(T_s - T_\infty)}{\mu_a^2} : \text{ Grashof number} \tag{29}$$

$$Pr = \frac{C_{Pa}\mu_a}{k_a} : \text{ Prandtl number} \tag{30}$$

where g (m s^{-2}) is the gravitational constant, β = 1/T is the coefficient of thermal expansion, T_s (K) is the temperature at the coated bread surface, k_a (W $m^{-1}K^{-1}$), and C_{Pa} (J $kg^{-1}K^{-1}$) are the thermal conductivity and specific heat of the air, respectively (data reported in Table 1).

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For the 2D axisymmetric model the local Nusselt number with downstream angular position of the bread surface is represented by the following equation:

$$Nu = Nu_\theta (GrPr)^{1/4} \quad (31)$$

Nu_θ values, as function of angular position was obtained by fitting the data graphically reported for sphere by Merk and Prins (1954).

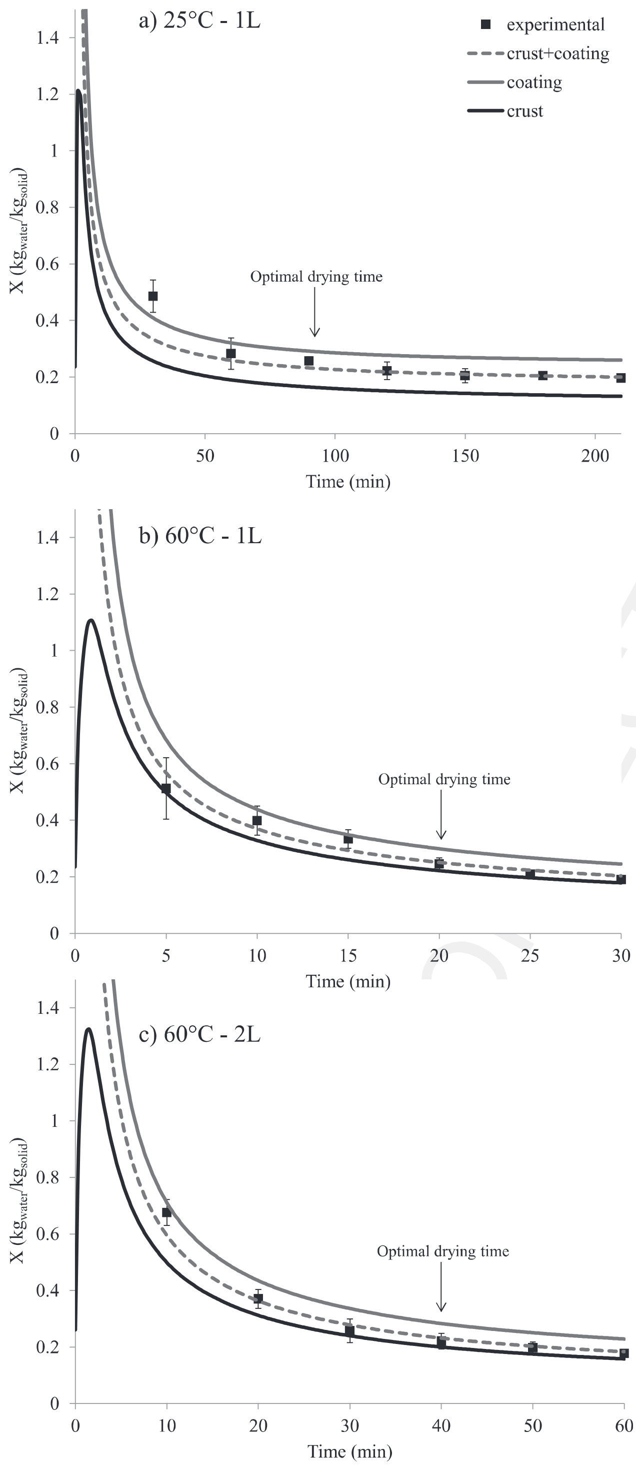

Fig. 2 – Experimental (●) and calculated (–) moisture content of the coating over the drying time at 25 °C and 60 °C (1L = 0.06 mm; 2L = 0.1 mm).

The average moisture content was calculated only for 1D model by the following equation:

$$\bar{C} = \frac{1}{d}\int_0^d C(x)dx$$

where d (m) and C_i (mol m^{-3}) are the thickness and the moisture concentration of the considered zone (crumb, crust and coating) as shown in Fig. 1.

2.2. *Model validation*

The model was validated comparing the average moisture content calculated and experimentally determined on the top and bottom surfaces of the samples (crust with coating).

For the experimental test, the bun bread samples characterised by the geometrical parameters reported in Fig. 2 were used. 2.5 and 4 g of edible coatings were coated on each bread by a brush for the samples with one layer and two layers respectively, obtaining a coating thickness of about 0.06 mm and 0.1 mm (calculated on the basis of ratio between volume and surface covered by the coating).

The coating solution was prepared with a mixture of pectin, alginate and whey protein concentrate 1.5% w/w each with the addition of 1.5% of glycerol and 0.16% Tween®20, used respectively as plasticiser and emulsifier. It was characterised by an initial moisture content of 93% (13 kg_{water} kg_{solid}^{-1}) and a water activity of 0.95. The coated breads were subsequently dried in a conditioned cabinet at 25 °C (RH = 65%) or at 60 °C (RH = 10%). The moisture content of the crust with coating was measured by heating 1 g of sample at 130 °C until constant weight, using a thermobalance (i-Thermo 163M, Exacta-Optech, Italy). Five bread samples for each time were taken into account.

Table 2 – Error between experimental and calculated moisture content ($kg_{water} kg_{solid}^{-1}$).

	ME	SD	RMSE	BIAS
25 °C – 1L	0.15	0.03 (0.02)	0.05 (0.03)	−0.03 (0.03)
60 °C – 1L	0.15	0.04 (0.03)	0.04 (0.03)	−0.01 (0.03)
60 °C – 2L	0.19	0.03 (0.01)	0.04 (0.03)	0.01 (0.04)

Note: ME = Maximum Error; SD = Standard Deviation; RMSE = 0.14Root Mean Square Error; BIAS.

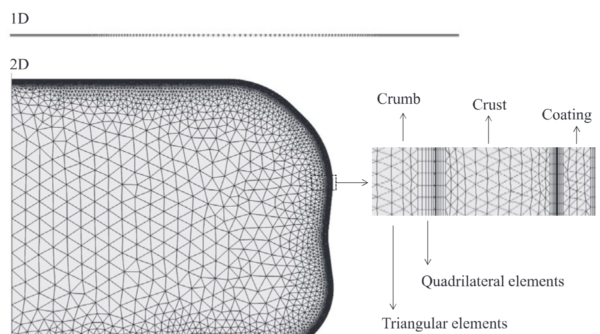

Fig. 3 – Mesh of the 1D and 2D axisymmetric models.

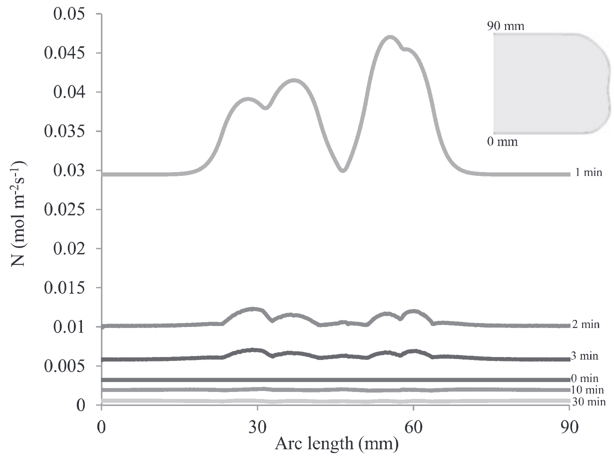

Fig. 4 — Mass flux calculated on the external boundary by using the 2D axisymmetric model, for different drying times (from 0 min to 30 min).

Maximum Error (ME), Root Mean Square Error (RMSE), Standard Deviation (SD) and BIAS were used to compare experimental and numerical data. RMSE, SD and BIAS were calculated as average of the values obtained for each time:

$$RMSE = \sqrt{\frac{\sum_i^n (X_{num} - X_{exp\_i})^2}{n}} \tag{32}$$

$$SD = \sqrt{\frac{\sum_i^n \left(X_{exp\_i} - \overline{X}_{exp}\right)^2}{n}} \tag{33}$$

$$BIAS = \frac{\sum_i^n (X_{num} - X_{exp\_i})}{n} \tag{34}$$

where X_{num}, X_{exp_i}, and $\overline{X}_{exp}$ are the calculated, experimental and average experimentally measured moisture content ($kg_{water} kg_{solid}^{-1}$), respectively. n is the number of the experimental replicates (5).

3. Results

3.1. Model validation

The results of models were experimentally validated comparing the experimental and calculated values (1D model) of the mean moisture content of the crust with coating (Fig. 2). Drying temperature of 25 °C (RH = 65%) and 60 °C (RH = 10%) were evaluated. For the experimental measurements, the average values and standard deviations calculated on five replicates (five breads) are shown. Concerning the drying at 25 °C, it can be seen that the moisture content tends to obtain equilibrium after about 150 min, when it reaches a value of 0.19 ± 0.01 kg_{water} kg_{solid}^{-1}. At this time, the coating water activity (0.66) is rather equal to the relative humidity of air in the cabinet (65%).

Fig. 5 — Moisture concentration field calculated at different points in time (0, 2, 5, 15, 10, 15 and 20 min) by using the 2D axisymmetric model (drying temperature of 80 °C) at the zone with the minimum (A) and maximum (B) value of mass flux.

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On the contrary, the coating moisture content of the samples drying at 60 °C appeared to decrease without reaching the equilibrium. This is due to the low relative humidity of the drying cabinet. The calculated data followed the same trend. ME, RMSE, SD and BIAS are reported in Table 2. A good agreement was obtained between calculated and experimental data reporting ME of 0.15, 0.15 and 0.19 $kg_{water}\ kg_{solid}^{-1}$

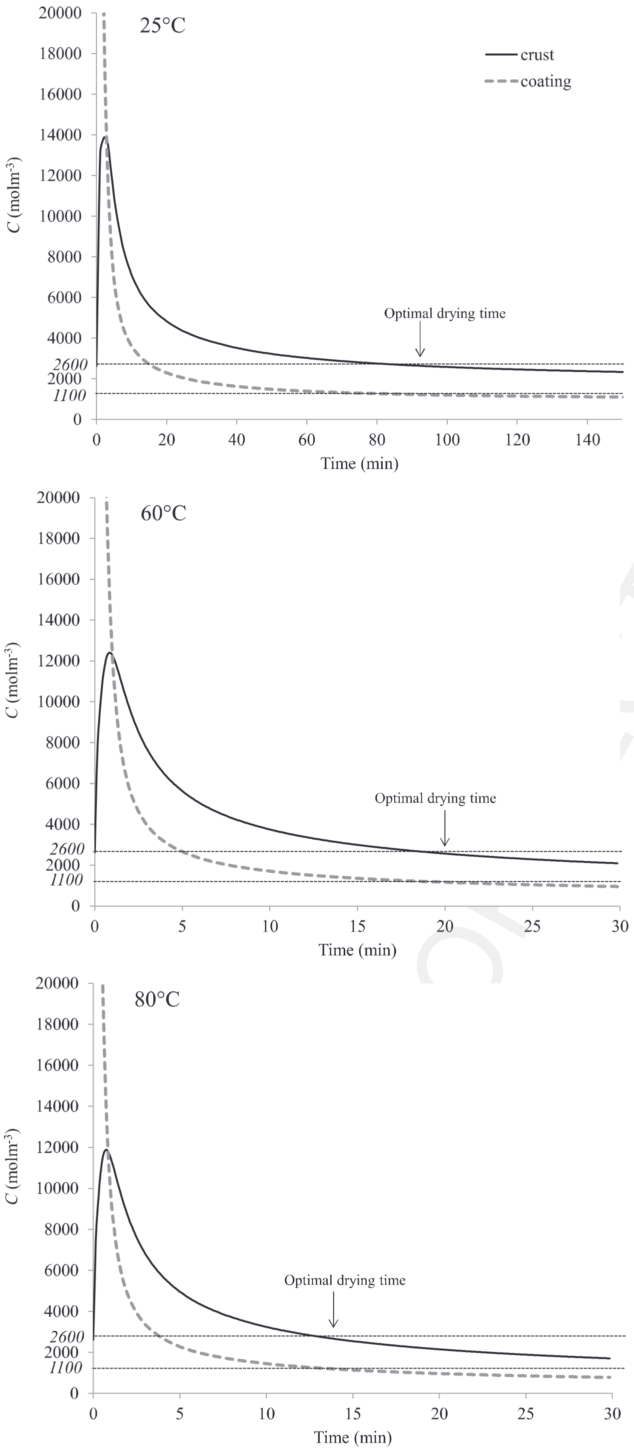

Fig. 6 – Average moisture concentration calculated at the coating and crust, over the time for 25, 60 and 80 °C of drying temperature.

and RMSE of 0.05, 0.04 and 0.04 $kg_{water}\ kg_{solid}^{-1}$ for the samples dried at 25 and 60 °C (one and two layer), respectively.

The BIAS and SD values allowed to evaluate the systematic error between calculated and experimental data and the random error between experimental measurements, respectively. In general, the lower BIAS values, suggest that the main component of the error is due to random errors related to experimental measurements. This could be due to the unsuitable technique of separation of the crust from the bread during the sample preparation.

Subsequently, the calculated optimal drying times were compared with those experimentally obtained. The optimal drying time was arbitrarily defined as the time necessary to remove the water from the coating until it reaches a moisture content of 0.28 $kg_{water}\ kg_{solid}^{-1}$ (about 1100 mol m^{-3}) corresponding to a water activity of about 0.75 (relative humidity of a hypothetic storage ambiente), avoiding the bread internal

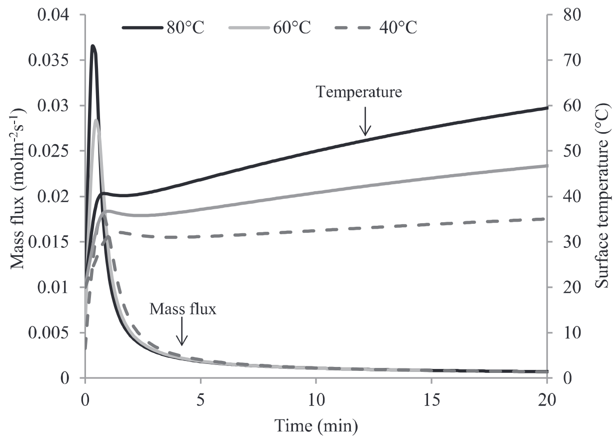

Fig. 7 – Mass flux and temperature calculated on the coated bread top surface over the time at different drying temperatures (40 °C, 60 °C and 80 °C).

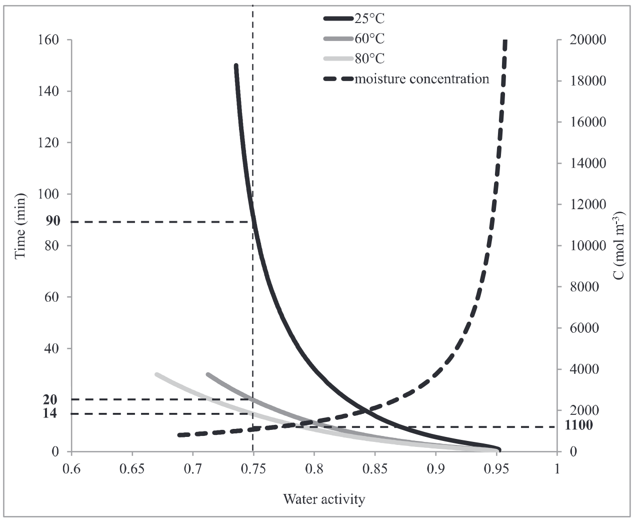

Fig. 8 – Calculated coating water activity over the time (25, 60 and 80 °C of drying temperature) and moisture concentration.

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dehydration. Accordingly, at the same time, the moisture content of the crust should be near to the initial value (0.23 $kg_{water}\ kg_{solid}^{-1}$, 2600 mol m^{-3}). Calculated optimal drying times were about 90, 20 and 40 min, for the samples dried at 25 and 60 °C (one and two layers), respectively. Analysing the experimental data, it was not possible to define an accurate time, but only a time range. However, the calculated times were observed to be within these ranges, confirming that by using the model it is possible to identify the correct optimal drying time.

3.2. *Model results*

For the 2D model, the meshed domain was composed by 111′275 triangular elements characterised by an average element quality (dimensionless quantity between 0 and 1, where 1 represents a perfectly regular element, and 0 represents a degenerated element) of 0.3788 and 14′645 quadrilateral elements placed on all boundaries (Fig. 3). 500 edge elements with a growth rate of 1.025 and an element length ratio of 0.002 have been selected for the 1D model. The computation was carried out on a PC with 24 CPU (Xeon5675 64 bit 3.07 GHz) and 24 GB RAM. The calculation time was about 3 s and about 250 s for the 1D and 2D models, respectively.

The mass flux (N) distribution on the coated bread surface was evaluated by using the 2D model (Fig. 4). It can be seen that the positions along the boundary have an important contribution on the N value approximately for the first 2 min (considering a drying temperature of 80 °C). After this time, the difference between the maximum and minimum N value appears to be negligible. The impact of the mass flux on the moisture concentration in the coating, crust and crumb, considering the bread zones where the minimum (A) and maximum (B) values of mass flux have been calculated, is shown in Fig. 5. Drying times of 2, 5, 10, 15 and 20 min have been considered (drying temperature of 80 °C, coating and crust thickness equal to 0.1 and 0.3 mm). At the same drying time, the moisture concentration profiles calculated in the A and B zones were almost equal, confirming that, for this geometry, the calculated mass flux difference does not significantly affect the moisture migration. Accordingly, the results of the 1D model were used for the following results discussion.

Crust and coating mean moisture concentrations (molm^{-3}), as function of the drying time (drying temperatures of 25, 60 and 80 °C), are reported in Fig. 6. The high difference between the moisture concentration of the coating and the crust drives the moisture movement from the coating to crust. At the same time, on the opposite front of the coating, the moisture evaporates.

Increasing the drying temperature, decreases the difference between the moisture concentration of the coating and the crust faster, thereby lowering the movement of the moisture in the crust. It can be seen that the moisture content of the crust passes from 2600 mol m^{-3} (0.23 $kg_{water}\ kg_{solid}^{-1}$) to 13′890 mol m^{-3} (1.25 $kg_{water}\ kg_{solid}^{-1}$) and from 2600 mol m^{-3} to 11′890 mol m^{-3} (1.07 $kg_{water}\ kg_{solid}^{-1}$) for the drying temperatures of 25 °C and 80 °C, respectively. Upon reaching the equilibrium between the coating and crust moisture content, the crust moisture starts to move towards the coating where the water evaporates. The rate of this motion depends on the diffusion coefficient of the moisture in the coating which is a function of the temperature and moisture content. Increasing temperature increases molecular mobility and diffusivity. Hence, it induces accelerated movement of water through the coating (Bourlieu, Guillard, Vallès-Pamiès, Guilbert, & Gontard, 2009).

The rate of this phenomenon also depends on the intensity of the starting mass flux (N) that is linearly correlated with the drying temperature ($N = 0.0001T\text{-}0.0359$; $R^2 = 0.999$) and of the gradient between the vapour relative humidity in the cabinet

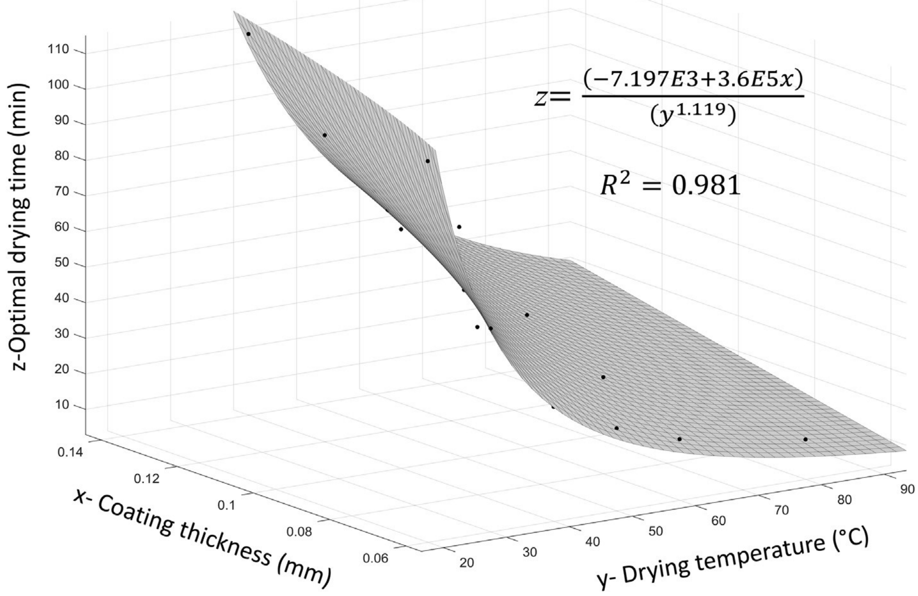

Fig. 9 – Regression between optimal drying time (min), drying temperature (°C) and coating thickness (mm).

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and the water activity at the interface (Fig. 7). Furthermore, because of the very small thickness of the coating, the major amount of the moisture content rapidly evaporates (coating moisture content decreases) causing a fast decrease in mass flux. The vapour evaporation energy causes a slowing down of the product temperature rise that starts to rapidly increase when the mass flux tends to decrease.

As described in the model validation section, the coating is arbitrarily considered dried when the coating water activity is comparable to relative humidity of the storage ambience (0.75 corresponding to 1100 mol m^{-3}) and the crust moisture concentration returns to the initial value (2600 mol m^{-3}, 0.23 $kg_{water}\ kg_{solid}^{-1}$). In this way, the coating water activity as function of the drying time and moisture concentration is reported in Fig. 8. It can see that the optimal drying time was reached after about 90, 20, and 14 min, for 25, 60 and 80 °C of drying temperatures, respectively. The same drying time was also identified evaluating the crust and coating moisture concentration over the drying time (see Fig. 6).

By using the model results, a relation between the optimal drying time (z), coating thickness (x) (0.06–0.14 mm) and the drying temperature (y) (from 25 to 90 °C) was determined (Fig. 9). Good results ($R^2 = 0.981$, 95% confidence bounds) were obtained by using an equation combining a linear relation between optimal drying time and coating thickness, and a power law relation between the optimal drying time and drying temperature $\left[z = \frac{(-7.197E3+3.6E5x)}{(y^{1.119})}\right]$.

In general, the estimated optimal drying time appears to be nearer to those reported in literature for coated bakery products (Bartolozzo et al., 2016; Bravin et al., 2006; Ferreira Saraiva et al., 2016; Noshirvani et al., 2017; Soukoulis et al., 2014). However, it is hard to have a direct comparison because of different product and coating characteristics as well as different drying conditions.

4. Conclusions

One dimensional and 2D axisymmetric finite elements models able to describe the heat and moisture transfer inside and on the surface of coated breads were developed to determine the proper coating drying time, in order to minimise the food internal dehydration. The 2D axisymmetric model, based on a real geometry, allowed to state that the influence of the surface temperature distribution on the mass flux is weak (drying temperature until 80 °C). The difference between the maximum and minimum mass flux value appeared to be negligible. The model was validated comparing the average moisture content calculated and measured on the coating of the breads dried at 25 °C and 60 °C. Good agreement was observed between experimental and numerical data (RMSE of 0.05 and 0.04 $kg_{water}\ kg_{solid}^{-1}$). The mean moisture contents calculated on the top and the bottom zones of the coated breads, as a function of the drying temperature, time and coating thickness, were taken into account. A specific relation between the optimal drying time, drying temperature and coating thickness was determined ($R^2 = 0.98$). The study demonstrated the feasibility of the model with particular reference to the approximations adopted, which can represent a good compromise between computational effort, reliability and generalization of results. The same model could be used for many other bakery products and coating formulations, simply by changing geometrical dimensions and the material properties. Q4

Uncited reference

Bitog et al., 2014, Purlis and Salvadori, 2009, Zhang and Datta, 2006. Q5

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