Modelling Heat and Mass Transfer in Band Oven Biscuit Baking

D. Fahloul, G. Trystram, A. Duquenoy and I. Barbotteau

D. Fahloul, G. Trystram, A. Duquenoy: Department of Food Process Engineering, ENSIA, 1, avenue des Olympiades, F-91305 Massy (France)
I. Barbotteau: BSN biscuits branch—centre Jean Thèves, BP 16, F-91207 Athis Mons Cedex (France)
(Received June 28, 1993; accepted September 28, 1993)

A steady state mathematical model which describes a natural gas indirect fired baking tunnel-oven is presented. Heat and mass transfer were studied. Individual heat transfer modes taken into account were radiation, convection and conduction. It was assumed that the baking chamber was homogeneous between roof and base. A homogeneous moisture and temperature distribution was assumed for the biscuit. The flow of air inside the oven and the drying of the biscuit were studied. A water activity model at high temperature was used. The model simulations provide spatial distributions of temperature and moisture of the biscuit, and temperature and hygrometry of the air. Experiments were performed at different baking conditions. Data were compared with numerical results. Good agreement was obtained between the experimental results and the model predictions.

Introduction

Baking is one of the most critical steps in ensuring the quality of bakery products. It is a traditional food process, based essentially on the experience of bakers.
Our objective is to develop a mathematical model, to study baking behaviour using simulation models. Since there are few measurements on industrial baking ovens, we want to use this model to extend experimental investigations of baking of different products in order to evaluate the impact of process variables such as temperature, air velocity and baking time. The model could be used in the development and control of ovens.
This paper describes the present state of the problem, materials and methods used (oven, probes) and equations of the model. Finally it draws comparisons between model predictions and experimental results.
There are many researchers who have investigated heat and mass transfer during the baking of bread and cakes (1,2). Previous studies on thermal and mass transfer in pastries, bread and cookies revealed the complexity of the baking of cereal products (3). Other investigators (4,5) studied experimentally the influence of air temperature and hygrometry on the characteristics of biscuits and bread.
In an oven, heat is transferred by conduction, convection and radiation. The differences in the percentage and combination of heat of each route account for the variation in baking results in different ovens (6,7).
Mathematical models for heat and mass transfer in baking processes have been developed (for example, 8–10). Until now, however, an efficiency model has not been developed, since there are different types of ovens, and so many differing types of products. The mathematical treatment of heat transfer is complex, since the properties of the product are continually changing during the process. The problem is also made more difficult since little information concerning the thermal properties of dough and biscuit material is readily available (11).
Few published studies are available on modelling industrial baking. Therefore, the modelling of related processes such as ceramic tunnel-furnaces, tunnel-dryers, have been studied (12–14). The aim of this work is to predict changes in the temperature and moisture profiles of oven and biscuit and to compare this model to a real tunnel-oven.

Material and Methods

Oven

The 15 m long pilot-scale oven is an indirectly fired multi-burner oven, heated with natural gas. It consists of four combustion chambers in the roof and base, equipped with 34 independently controlled ribbon burners. The baking chamber can be separated into six zones by paddles (**Fig. 1**), and is equipped with a wire mesh band of 0.65 m width. Each zone has independently controlled roof and base temperature, the baking atmosphere (steam, volatile products) can be drawn out of the baking chamber through five exhaust ducts, fitted with variable-rate fans. Each fan can be independently varied. The velocity in the chimneys was fitted by a quadratic model, so we can estimate the velocity through the five exhaust ducts at any specified fan rate.

0023-6438/94/020119 + 06 $08.00/0

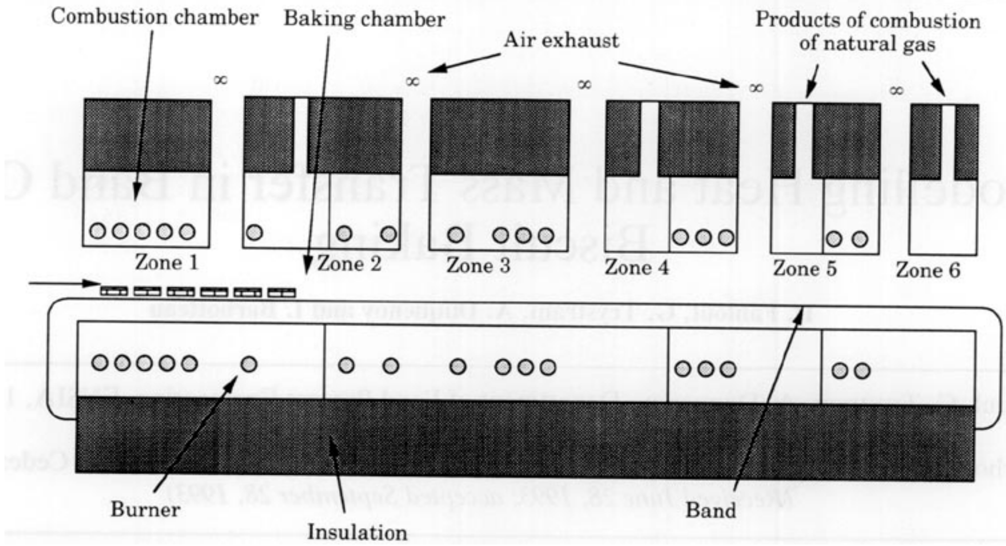

Fig. 1 Simplified description of natural gas indirect fired pilot oven

Biscuits

Biscuits were the product used in this study. Typical ingredients were: 100g flour, 26g sugar, 22g water, 10g butter, 2.5g BCA, 0.8g BCS, 0.7g salt with a production rate of 161 kg/h, and baking times of 6 to 8 minutes.

Measurements

The air temperature, the humidity of the baking chamber, the temperature and the weight change of biscuits were measured under different conditions, obtained by varying the eight temperature set-points in the baking zones in roof and base and the power of air extraction in the five chimneys.

The humidity of the air was measured by an Hygrophil probe H (Ultrakust Society) at a number of points through the oven. The air temperature was measured in five locations in the oven by a Thermophyl probe (Ultrakust Society) which travelled through the oven with the band and biscuits (**Fig. 2**). The temperature of the biscuit was measured by one of the thermocouples of the thermophyl. Measurements were taken every 6s. The weight loss of the individual biscuits were measured by samples taken along the oven (seven samples).

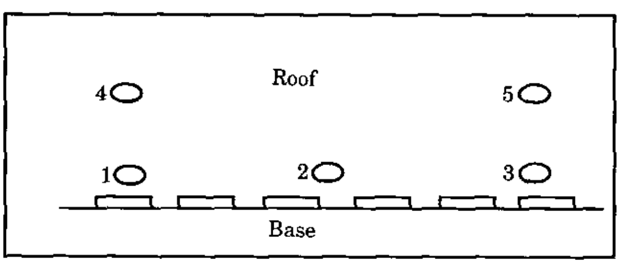

Fig. 2 Measuring positions of the air temperature in baking chamber with thermophyl apparatus

Mathematical Model

The baking process is viewed as a process of simultaneous mass and energy transfer occurring both inside and outside the product. The oven is subdivided into compartments. Inside each compartment, the rate flow of dry air is constant. Three parts are recognized: biscuit, air and band conveyor. Internal wall temperatures were assumed to remain constant. The forms of heat transfer taken into account are radiation, convection and conduction.

In obtaining the following set of differential equations the following assumptions were made:

1. The model is steady state.
2. Mass and energy transport occur in only one dimension.
3. The elements of the oven are assumed to be grey bodies for radiation.

Equations

Biscuit. Moisture balance,

$$m_b.\frac{dX_b}{dx} = -m_{vap} \qquad \text{Eqn (1)}$$

where m_b is the rate of product throughput, X_b is the product moisture, x is the space dimension and m_{vap} the rate of evaporated water.

Heat balance,

$$m_b.cp_b.\frac{dT_b}{dx} = a_6.h_b.(T_a - T_b) + (1 + por).a_7.(qa_b - \varepsilon_b.\sigma.T_b^4) + (1 - por).a_7.k_{tb}.(T_t - T_b) - m_{vap\cdot b}.\Delta H_{vap}.(T_b) \qquad \text{Eqn (2)}$$

where cp_b is the specific heat of biscuit, h_b is the convective exchange coefficient, ΔH_{vap} the latent heat of vaporization, k_{tb} is the exchange coefficient between biscuit and the band, T_t is the temperature of the band, *por* its porosity, and qa_b is the heat flux absorbed by the biscuit, calculated by the radiosities method. This method requires a knowledge of view factors in the oven, obtained geometrically on charts given by Knudsen (15), and of correlation between emissivity and absorptivity of the air and its temperature and humidity (16,17).

Air. The flow rate of dry air da_i is constant between two chimneys $i-1$ and i. For the point corresponding to a chimney we have:

$$\text{for } i < jf \qquad da_{i+1} = da_i - d_{ext}(i) \qquad \text{Eqn (3)}$$

where $d_{ext}(i)$ is the flow rate of dry air extracted from the chimney i.
We assume that there is a chimney jf where the flow of air changes from the co-current flow to the counter-current flow.

$$\text{for } i > jf \qquad da_{i-1} = da_i - d_{ext}(i) \qquad \text{Eqn (4)}$$

In order to find the flow rate of dry air which enters on the two sides of the oven, we established an overall mass balance. We then assumed that half of the total dry air rate entered on each side.

Moisture balance,

$$da_i.\frac{dY_a}{dx} = m_{vap} \qquad \text{Eqn (5)}$$

where Y_a is the air humidity on dry basis.

Heat balance,

$$\begin{aligned} da_i.cp_a.\frac{dT_a}{dx} = &-(l_a.h_1.((T_a - T_{ph}) + (T_a - T_{pb})) + \\ &2.e_a.h_1.(T_a - T_{pl}) + a_5.h_1.(T_a - T_t) + \\ &a_6.h_b.(T_a - T_b)) + l_a.(qa_a - \varepsilon_a.\sigma.T_a^4) + \\ &m_{vap}.cp_{vap}.(T_b - T_a) \end{aligned} \qquad \text{Eqn (6)}$$

where cp_a is the specific heat of air, l_a is the width of baking chamber and e_a its height, h_1 is the convective exchange coefficient, T_{ph}, T_{pb}, T_{pl} are the temperatures of the respective oven walls.

Band conveyor. Heat balance,

$$\begin{aligned} m_t.cp_t.\frac{dT_t}{dx} = &a_5.h_1.(T_a - T_t) + a_5.(qa_t - \varepsilon_t.\sigma.T_t^4) - \\ &(1 - por).a_7.k_{tb}.(T_t - T_b) \end{aligned} \qquad \text{Eqn (7)}$$

with: $m_t = s_t.v_t.\rho_t$

where v_t is the conveyor speed, ρ_t is its density, s_t is its section.

Modelling mass transfer fluxes
The mass transfer fluxes in the biscuit are described so as to take account of three different modes of transfer: condensation of steam on the surface of the biscuit at the inlet, convection drying and then boiling drying (10). In this previous study a water activity model was calculated at 20 °C. Water activity is an important parameter to describe the interaction between the process and products. During baking a_w changes with starch gelatinization, melting of fat, dissolution or crystallization of some products (salt, sugar) and Maillard reaction.
Previous work was done using a model of water activity which was obtained for dough at low temperature. Extrapolation was necessary to have a continuous model of water activity (10). Recent results establish a new method for measurements of water activity at high temperature (18). The Oswin model is fitted with data performed in our laboratory by Bassal and Vasseur (18), for the product formulation described above. This model is valid between 90 °C and 150 °C

$$a_w = \frac{1}{1 + \left(\frac{ka}{100.X_b}\right)^{(1/kb)}} \qquad \text{Eqn (8)}$$

where:

$ka = 18.747 - 0.107.T_b$
$kb = 0.889 - 0.0024.T_b$

Thermophysical properties
The values of the physical properties were obtained from the literature. For air, models of specific heat, density, heat conductivity and viscosity based on composition and temperature were used (16). However, published thermophysical properties of biscuits are scarce. Rask (11) published a review of data of thermal properties of dough and bakery products. The exchange coefficient between biscuits and band conveyor was taken to be 35 W/(m^2.K) (6). The density of biscuits was taken to be 946 (kg/m^3) and their specific heat was taken to be $cp_b = 1680 + 4180.X_b$. The biscuit latent heat of vaporization is temperature dependant. A more accurate description would be possible if a more accurate model was used. The transfer coefficients have been correlated elsewhere (10) with dimensionless groups such as Reynolds number and Prandtl number. To use them for another kind of oven or another configuration, it would be necessary to validate these correlations for the particule conditions pertaining. The convective exchange coefficient between air and biscuit was taken to be between 10 and 20 W/(m^2.K). The maximum value of this coefficient was estimated to be 20 W/(m^2.K) in the same oven (10). The mass transfer coefficient was taken to be between 2×10^{-8} and 4×10^{-8} kg/(m^2.s.Pa).

Method of solution
A system of five first-order differential equations, with nonlinearities in each equation due to the radiation terms was used. The equations were also coupled as a result of evaporation and drying. The 4th order Runge Kutta method was used to solve this system. Solutions take into account the co-current and the counter-current flows of air.

Results and Discussion

The measured variables are temperature and moisture of the biscuit as well as temperature and humidity of the baking chamber. Examples of the recording of the biscuit temperature measured at different baking conditions are shown in **Fig. 3**. In each case the temperature rises continuously. It could be observed, for example for the test at 250 °C, that the burners have an influence on the biscuit temperature. Radiative heat transfer in the combustion chamber implies heterogeneity of upper wall temperature. As a consequence the biscuit temperature is disturbed. Another influence is the presence of the chimney. At a low temperature (150 °C), the temperature rise of the biscuit stopped at a value less than 100 °C, but for a higher temperature in the baking chamber (200, 250 °C), the internal temperature of the biscuit is higher than 100 °C. This is probably due to boiling drying mode. However Hasatani *et al.* (2) showed that at different baking conditions the internal temperature of bread stopped at 100 °C. Similar results are available for bread (19).

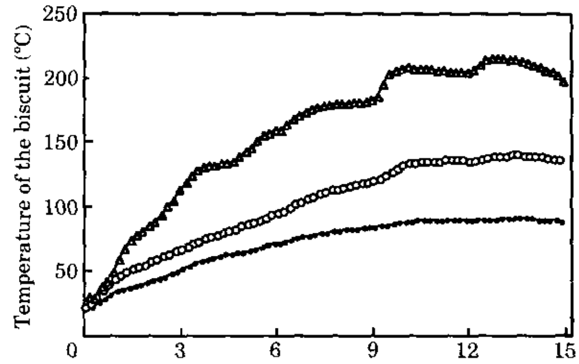

Fig. 3 Influence of air temperature on biscuit temperature evolution versus oven length; velocities in the chimneys: 1.77, 2.97, 1.33, 1, 1 (m/s). (●) 150 °C; (○) 200 °C; (△) 250 °C

The weight loss of biscuits for baking temperatures 150, 200, 250 °C is shown in **Fig. 4**. Baking temperature has a significant effect on the weight loss of the biscuit, and a constant drying rate was not observed.

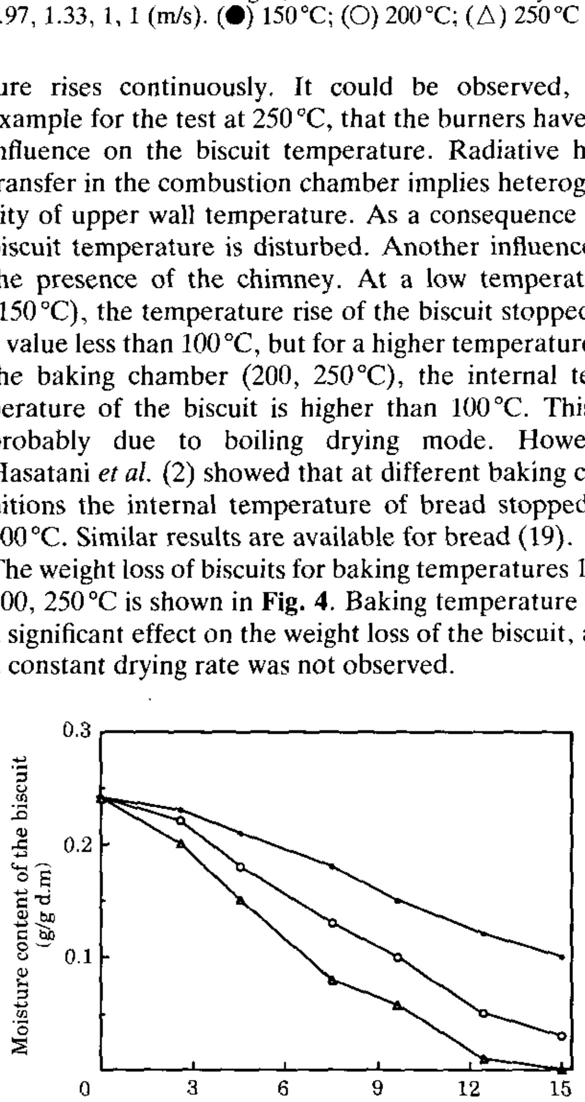

Fig. 4 Influence of air temperature on biscuit moisture evolution versus oven length; velocities in the chimneys; 1.77, 2.97, 1.33, 1, 1 (m/s). (●) 150 °C; (○) 200 °C; (△) 250 °C

Computer simulations were carried out for different oven temperatures and velocities. In order to test the predictions of the model, comparisons were made with the experimental data. Some comparisons are shown in **Figs 5** and **6**. Experimental conditions are shown on each graph.

As can be seen, a good agreement is obtained between the results of the model and the experiments. The comparison of biscuit temperatures is in good agreement (**Fig. 5a**). During the later period of baking, the simulation results predict lesser values than those obtained experimentally. This is probably due to the accuracy of temperature measurement and to some interactions on the biscuit which are not described (for example, crust formation).

The predicted moisture content of biscuit is in good agreement with experiments (**Fig. 5b**). The qualitative behaviour of simulated values is good and in conformity with classical understanding of biscuit drying. The quantitative result is also good. Differences between the calculated curves and experimental data may be due to the accuracy of the water activity model or to the influence of air temperature variation. However we notice that while the baking of biscuits includes drying, biochemical and the physical transformation of the product, the model describes only the drying phenomena.

For the air temperature there is an agreement between the model and the experiment during approximately three quarters of the baking process (**Fig. 6a**). In the final quarter, the simulation results predict higher air temperature than those obtained by measurement. This was due to repartition of the air flow which enters on two sides of the oven. The simulated air temperature profile was homogeneous since we assumed a constant internal wall temperature. However experiments showed that some burners created an heterogeneous temperature profile on the internal wall surfaces. Therefore we observed fluctuations in the experimental air temperature. Moreover, the air temperature was not constant in the cross section of the baking chamber. The peaks that we observed in the experimental air temperature were due to hot zones near the chimneys.

For the air hygrometry (**Fig. 6b**), the comparison between the simulation results and experimental data were not so good. Air humidity is measured in the air above the band conveyor at seven points along the oven, and we have approximately one measured point every 2 m, which is not enough. Thus the difference could be attributed to linear interpolation between the experimental data of air hygrometry and to the true air velocity profile in the oven. Hence, the distribution of moisture in the baking chamber was strongly affected by the degree of air movement resulting from natural or forced convection (20).

In order to represent the prediction error of the model, **Fig. 7** presents the comparison between predicted and measured moisture content of biscuit. There is good agreement characterized by a close linear relationship between simulation results and experimental data of biscuit moisture. The error is less than 5%. The difference between the experimental data and the mathematical model could be attributed to a number of reasons:

1. Experimental difficulties, such as the displacement of the thermocouple used to measure the product temperature (thin product);

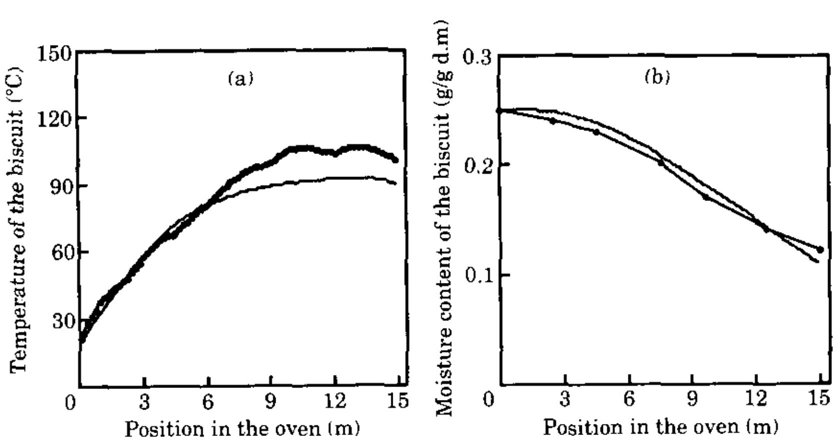

Fig. 5 Moisture and temperature profiles of the biscuit for the following conditions: air temperature set point 150°C; velocities in the chimneys: 1, 1, 1.33, 2.97, 1.77 (m/s). (●) Measured; (——) simulated

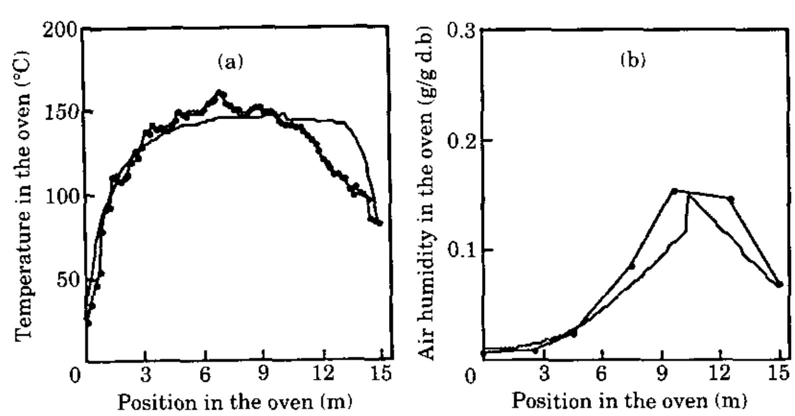

Fig. 6 Humidity and temperature profiles in the baking chamber for the following conditions: air temperature set point 150°C; velocities in the chimneys: 1, 1, 1.33, 2.97, 1.77 (m/s). (●) Measured; (——) simulated

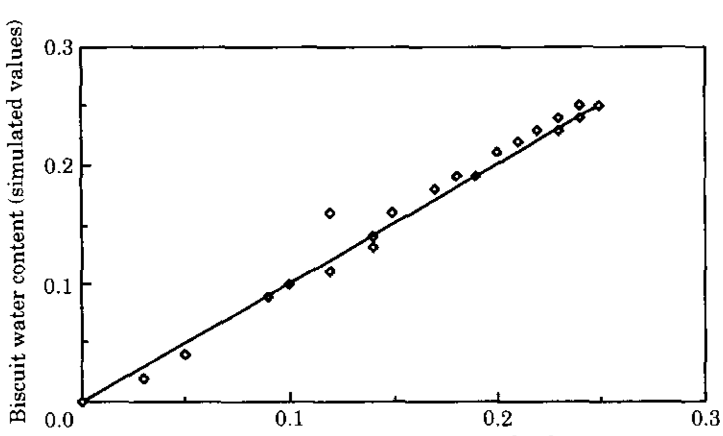

Fig. 7 Comparison of simulation results with experimental data of biscuit moisture

2. Lack of precise knowledge of some properties of the product which change during the baking process (density, specific heat) and errors in physical (thermal) property values used for simulation purposes;
3. Influence of external conditions around the oven which influence the reproducibility of experimental results.

Despite these difficult conditions which are often encountered in real scale studies, the relative error of the model appears to be less than 7%. This is a good result in order to study the influence of operating conditions, and oven design on the baking of biscuits.

The presented mathematical modelling is a macroscopic baking model which does not depict heat and mass transfer occurring within the biscuit. It is also possible to include an additional microscopic model of the biscuit. This macroscopic baking model serves as an approximate tool for design and development work (e.g. process scaling, equipment sizing, monitoring).

Conclusions

A mathematical model of the baking of biscuits in a tunnel-oven has been developed which gives good prediction of temperature and moisture, both for biscuit and air, in the oven.

The model developed has the advantage of being

simple. It can be fitted to another type of oven and other type of products, for example, by changing the characteristics of the oven (dimensions, type of materials), or those of the product (dimension, thermophysical properties).
The comparison between the model and the experimental results is in good agreement, so the model can be used to predict other oven conditions. However, some problems still remain such as the low air velocity in the oven and the repartition of the air flow on the two sides of the oven.

Nomenclature

a_5:	Exchange surface between biscuits and band conveyor per unit of length	(m)
a_6:	Exchange surface between biscuits and air per unit of length	(m)
a_7:	Upper exchange surface between biscuits and air per unit of length	(m)
aw:	Water activity	
cp:	Specific heat at constant pressure	J/(kg.K)
da:	Rate of flow of dry air	(kg/s)
d.b:	Dry basis	
$d_{ext}(i)$:	Rate of flow of dry air extracted from the chimney i	(kg/s)
d.m:	Dry matter	
e_a:	Height of the baking chamber	(m)
h_1:	Heat transfer coefficient	(W/(m^2.K))
h_b:	Heat transfer coefficient between air and biscuit	(W/(m^2.K))
k_{tb}:	Heat transfer coefficient between band and biscuit	(W/(m^2.K))
l_a:	Width of the baking chamber	(m)
m_b:	Rate of dried biscuits	(kg/s)
m_{vap}:	Rate of evaporated water	(kg/(m.s))
por:	Band porosity	
qa:	Absorption heat flux	(J/(m^2.s))
T:	Temperature	(K)
v_t:	Conveyor speed	(m/s)
x:	Space variable	(m)
X:	Moisture content of biscuit on dry basis	(kg/kg)
Y:	Air humidity on dry basis	(kg/kg)
ε:	Emissivity coefficient	
σ:	Stephan Boltzman constant	
ΔH:	Latent heat of vaporization	(J/kg)
ρ:	Density	(kg/m^3)

Subscripts

a:	Air
b:	Biscuit
t:	Band conveyor
ph, pb, pl:	Walls of the oven
vap:	Vapour

References

1 SLUIMER, P. AND KRIST-SPIT, C. E. Heat transport in dough during the baking of bread. In: NORTON, I. D. (Ed.), *Cereal in a European Context.* Chichester: Ellis Horwood Pub., pp. 355–363 (1987)

2 HASATANI, M., ARAI, N., KATSUYAMA, H., HARUI, H., ITAYA, N., FUSHIDA, N. AND TATSUKAWA, N. Heat and mass transfer in bread during baking in an electric oven. In: MUJUMDAR, A. S. AND FALKOVA, I. (Eds), *Drying '91.* Amsterdam: Elsevier Science publishers, pp. 385–393 (1991)

3 AUDIDIER, Y. Effects of thermal kinetics and weight loss kinetics on biochemical reactions in dough. *Bakers' Digest*, **10**, 36–42 (1968)

4 BRUNET, P., TRYSTRAM, G., MARCHAND, B., LAMBERT, D. AND RAPEAU, F. Profils thermiques et hygrométriques dans les fours industriels de cuisson de produits céréaliers. *Industries Alimentaires et Agricoles*, **10**, 891–900 (1987)

5 RASK, C. The heat transfer in a convection oven—influence on some product characteristics. In: *Cereal Science and Technology in Sweden*, proceedings of an international symposium, Sweden (Juin 13–16) (1988)

6 STANDING, CH. Individual heat transfer modes in band oven biscuit baking. *Journal of Food Science*, **39**, 267–271 (1974)

7 PALOHEIMO, M., MALKI, Y. AND KAUALUOTO, S. Optimisation of baking process: combined heat transfer. In: ZEUTHEN, P. (Ed.), *Thermal Processing and Quality of Foods.* London: Elsevier Applied Science Pub., pp. 487–491 (1984)

8 KAISER, V. A. Modeling and simulation of a multi-zone band oven. *Food Technology*, **12**, 50–53 (1974)

9 HAYAKAWA, K. AND HWANG, P. Apparent thermophysical constants for thermal and mass exchanges of cookies undergoing commercial baking processes. *Lebensmittel-Wissenschaft und-Technologie*, **6**, 336–345 (1981)

10 SAVOYE, I., TRYSTRAM, G., DUQUENOY, A., BRUNET, P. AND MARCHIN, D. Heat and mass transfer modelling of a biscuit baking oven, part 1; modelling principle and equations. *Journal of Food Engineering*, **16**, 173–196 (1992)

11 RASK, C. Thermal properties of dough and bakery products: a review of published data. *Journal of Food Engineering*, **9**, 167–193 (1989)

12 ETCHEVERRIA LARRAZABAL, A. Identification et optimisation d'un four d'industrie céramique. Thesis, University Paul Sabatier, Toulouse (1985)

13 BARRETEAU, D. AND BABARY, J. P. Modélisation de fours tunnels dans l'industrie céramique. *Entropie*, **119**, 34–39 (1984)

14 BERTIN, R. Analyse, modélisation, identification et optimisation du processus de séchage. Thesis, University Bordeaux I, Bordeaux (1984)

15 KNUDSEN, J. G. Heat transmission. In: PERRY, R. H. AND GREEN, D. W. (Eds), *Perry's Chemical Engineers Handbook.* New York, U.S.A.: McGraw-Hill Pub., pp. 10–52 (1984)

16 MUREAU, P. AND BARRETEAU, D. Modélisation d'un four à rouleaux. Document interne Gaz de France-DETN, Paris (1981)

17 SAVOYE, I. Etude et modélisation d'un four-tunnel de biscuiterie à chauffage indirect au gaz naturel. Thesis, ENSIA, Massy, France (1993)

18 BASSAL, A. AND VASSEUR, J. Measurement of water activity at high temperature. In: MUJUMDAR, A. S. (Ed.), *Drying '92.* Amsterdam: Elsevier Science Publishers, pp. 313–321 (1992)

19 ZANONI, B., PERI, C. AND PIERUCCI, S. A study of the bread-baking process. 1: A phenomenological model. *Journal of Food Engineering*, **19**, 389–398 (1993)

20 MCFARLANE, I. Measurement of humidity in baking ovens. In: ASCHWORTH, J. C. (Ed.), *Proceedings of the Third International Drying Symposium.* Birmingham: Drying Research Ltd, Pub., pp. 212–218 (1982)