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Determination of the Thermal Diffusivity of Bread as a Function of Porosity

B. Zanoni, C. Peri & R. Gianotti

DISTAM, Sezione Tecnologie Alimentari, Università di Milano, Via Celoria, 2-20133 Milano, Italy

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ABSTRACT

Experiments were carried out to determine the thermal diffusivity and the apparent density of bread crust and crumb as a function of porosity. The thermal diffusivity was determined by comparing the temperature profile obtained experimentally during heating of bread at 100°C in an oven and the temperature profile calculated using a computer program to simulate heat transfer inside the product. Experimental measurements showed that the apparent density ρ *(kg/m*^{3}*) of the crumb and the crust follows a linear trend as a function of porosity* ε*(%):*

For the crumb: $\rho = 979 - 9{\cdot}90\ \varepsilon$

For the crust: $\rho = 895 - 9{\cdot}0\ \varepsilon$

The thermal diffusivity α *(m*^{2}*/s) follows an exponential trend as a function of porosity:*

For the crumb: $\alpha = \exp(0{\cdot}01\varepsilon - 15{\cdot}25)$

For the crust: $\alpha = \exp(0{\cdot}0062\varepsilon - 15{\cdot}30)$

INTRODUCTION

This research is part of a study on baking modelling; a mathematical model of bread baking has already been set up (Zanoni *et al.*, 1993, 1994). To solve this model, mathematical relationships have to be defined, which describe the variation in the thermophysical properties of the product during baking as a function of operating conditions and product structure. Apparent density, specific heat, thermal conductivity and thermal diffusivity are the most important thermophysical properties during baking.

Table 1 (Rask, 1989) shows the values reported in the literature for the above thermophysical properties for doughs and baked products. It can be

TABLE 1
Thermophysical Properties of Baked Products

Product	*Temperature (°C)*	*Moisture content (%)*	*Apparent density (kg/m^3)*	*Specific heat (J/kg K)*	*Thermal conductivity (W/m K)*	*Thermal diffusivity (m^2/s) $\times 10^{-8}$*
Wheat bread dough	28	42·0	623	2883	0·414	23·0
	—	44·4	750	2800	0·500	23·8
	—	44·8	586	2801	0·314	19·0
	—	45·1	629	2805	0·327	18·5
Rye bread dough	—	45·9	820	3000	0·600	24·4
	—	53·6	718	3023	0·407	18·7
	—	53·9	701	3027	0·396	18·7
Biscuit dough	—	4·1	1252	2940	0·405	11·0
	—	8·5	1287	2804	0·390	10·8
Bread crumb	18	41·8	402	3190	0·298	23·2
	—	42·5	545	2742	0·248	16·6
	18	42·8	340	2975	0·244	24·1
	—	44·4	450	2800	0·280	22·2
	—	45·0	500	2805	0·232	16·5
Bread crust	120	0·0	300	1470	0·066	15·0
	—	0·0	417	1680	0·055	7·85
	—	0·0	420	1675	0·055	7·81
Cake	—	35·5	694	2950	0·223	10·9
	—	41·5	300	2800	0·121	14·4

seen that the mean value for the apparent density of bread dough is about 700 kg/m^3, whereas the mean value for baked bread is much lower (about 400 kg/m^3) for both the crust and the crumb. During baking the apparent density of bread decreases due to both the increase in the product volume and the decrease in the water content. At the end of baking, the crust has a low water content and a firm, non-porous structure; as a result, its apparent density values are similar to those for the crumb, which is wetter and more porous.

General models (Miles *et al.*, 1983; Toledo, 1991) are reported in the literature, which allow the apparent density of any food product to be calculated as a function of the chemical composition, moisture, porosity and temperature. In addition, semi-empirical (Hwang & Hayakawa, 1980) and empirical models (Bakshi & Yoon, 1984) are available, which describe the variation in the apparent density of baked products, such as cookies and bread rolls, as a function of the variation in temperature, moisture and baking time.

The specific heat depends on the chemical composition, temperature and, above all, moisture. Table 1 shows that the average specific heat of the dough and the crumb is about 2900 J/kg K, whereas the average specific heat of the crust is about 1600 J/kg K. General models (Miles *et al.*, 1983) have also been set up for the specific heat. They describe the variation in the specific heat of food products as a function of the variation in chemical composition, moisture and temperature. For baked products, semi-empirical models, such as the model of Bakshi and Yoon (1984) for bread rolls and that of Christenson *et al.* (1989) for bread, muffins and biscuits, describe the variation in the specific heat with moisture.

Johnsson and Skjoldebrand (1984) and Zanoni and Petronio (1991) set up semi-empirical models for the specific heat of bread as a function of moisture and temperature. The former showed a difference in behaviour between the crust and the crumb whereas the latter showed that the specific heat of the crust and the crumb can be described by the same equation.

Table 1 shows that the average thermal conductivity of bread dough is about 0·4 W/m K, and about 0·2 and 0·06 W/m K for the crumb and the crust, respectively. This depends on the fact that the thermal conductivity varies as a function of moisture, apparent density and, therefore, porosity. The models reported by Miles *et al.* (1983) allow the variation in the thermal conductivity to be predicted as a function of the chemical composition, moisture and temperature of foods, but they are not adequate to predict the thermal conductivity of porous products. Semi-empirical models for baked products are also reported in the literature. They allow the prediction of the thermal conductivity as a function of moisture and apparent density (Bakshi & Yoon, 1984) and as a function of moisture and temperature (Christenson *et al.*, 1989). Most thermal diffusivity values reported in the literature are directly evaluated from values for apparent density, thermal conductivity and specific heat. The mean values for thermal diffusivity shown in Table 1 are 18×10^{-8} m^2/s for doughs and the crumb and 10×10^{-8} m^2/s for the crust. Such values depend on the combined effects of moisture and porosity on the values for apparent density, thermal conductivity and specific heat.

De Vries *et al.* (1989) showed that the thermal diffusivity of leavened dough and porous crumb is higher than that of gas-free dough and firm crumb. This is in disagreement with the practical observation that porosity does not facilitate, but rather hinders transport phenomena. To explain this result, De Vries *et al.* (1989) hypothesize that heat and mass transport inside the product is controlled by a mechanism of water evaporation–condensation inside the product pores not by a mechanism of conduction and diffusion.

The aim of this work is to determine both the thermal diffusivity of bread crust and crumb as a function of porosity and a relationship between thermal diffusivity and porosity, thus confirming or refuting the hypothesis of De Vries *et al.* (1989).

MATERIALS AND METHODS

Tests were carried out on commercial French type bread crumb (Panem s.r.l., Milan, Italy). The chemical composition of the bread is shown in Table 2. Cylindrical crumb samples (diameter 72 mm) were obtained from loaves of bread (about 1 kg) and placed into cylindrical tin plate containers (height 54 mm, diameter 72 mm, wall thickness 0·25 mm). In order to simulate transport conditions occurring in the crust, the crumb samples, placed in the cylindrical container, were dehydrated by drying in an oven at 102°C until reaching constant weight. The samples obtained were sealed with a lid and used to determine the thermal diffusivity.

Chemical analyses

The following analyses were carried out in duplicate on the samples: Moisture content (%) was determined by drying 5 g of ground sample in an oven at 102°C until reaching constant weight. Total protein content (%) was determined on 0·5 g of sample by the Kjeldhal method using 5·7 as conversion factor. Lipid content (%) was determined by extraction carried out on 5 g of dried, ground sample with petroleum ether using the rapid Soxhlet method (Soxtec System HT2 1045, Tecator, Sweden). Ash content (%) was determined on 7 g of dried, ground sample by calcination in a muffle oven at 550°C for 6 h. Carbohydrate content (%) was determined by difference.

TABLE 2
Chemical Composition of Bread Crumb Samples (%)

Moisture content (%)	46·0
Carbohydrate content (%)	44·8
Total protein content (%)	7·0
Ash content (%)	2·0
Lipid content (%)	0·2

Measurement of porosity

The following method was used to prepare crust and crumb samples with different porosities. Porosity can be described as the ratio between the volume of the pores (i.e. total volume less volume of solid material) and the total volume of the product (Unklesbay *et al.*, 1981):

$$\varepsilon = \frac{V_t - V_v}{V_t} \tag{1}$$

where

V_t=total volume of the sample,
V_v=volume of non-porous material (i.e. solids) in the sample.

This variable can be measured on samples having a defined shape by compression with an Instron Testing Machine dynamometer (mod. 4301, Instron, Milan, Italy), which allows pores to be completely removed. The compression experimental conditions applied to samples were as follows:

— maximum compression load 10 kg,
— compression rate 100 mm/min,
— initial height of the sample 54 mm,
— constant diameter of the sample 42 mm.

Since the sample diameter is constant, the equation of porosity can be written as follows:

$$\varepsilon = \frac{H_o - H_f}{H_o} \tag{2}$$

where

H_o=initial height of the sample (mm),
H_f=final height of the sample (mm) after compression.

Original crumb samples, obtained from loaves of French type bread, at 79% mean porosity were used to prepare samples with different porosity. Crumb samples having different heights were placed into the tin plate containers used to measure the thermal diffusivity and compressed. Samples at 0, 20, 24, 37, 48, 50, 71 and 79% porosity were prepared.

Measurement of thermal diffusivity

The method used to determine the thermal diffusivity α of bread crust and crumb as a function of porosity is based on the comparison between temperature profiles detected during heating of samples and temperature profiles obtained from modelling of heating. The thermal diffusivity was determined on crumb samples with 46% moisture content and 0, 24, 37, 50, 71 and 79% porosity. The samples were sealed in tin plate containers and heated to 100°C in a forced convection pilot air oven (Carlo Erba S.p.A., Milan, Italy). The same method was applied to determine the α of crust samples at 0, 20, 48 and 71% porosity.

The temperature of the samples during heating was measured using a type T thermocouple (diameter 2 mm), which was placed at the geometric core of the sample. A data acquisition system (Datascan 7720, Datagest s.r.l., Milan, Italy), interfaced to PC by RS 232, allowed the temperature profile to be determined.

The mathematical model of the temperature profile at the geometric core of the samples is based on the following assumptions:

- the sample is only affected by the heat transfer phenomena; mass transport does not occur because the tin plate container is sealed. Since the sample has already been baked, there are no changes in porosity and no heat effects due to starch gelatinization;
- heat is transferred by forced convection to the container surface and by conduction through the container walls; heat is transferred inside the sample by unsteady state conduction;
- since the sample was hanging in the oven, it can be assumed that heat transfer is two-dimensional;
- a finite cylindrical shape is assumed;
- it is assumed that apparent density and thermal diffusivity are constant during heating and that the sample is homogeneous with respect to these properties.

The following equation describes the heat transfer at the surface of samples:

$$\frac{\mathrm{d}T_s}{\mathrm{d}t}=\left(\frac{\left(\frac{h_{tot}(T_{ext}-T_s(I,J))}{\mathrm{d}x}+\frac{\lambda \mathrm{d}^2T}{\mathrm{d}x^2}+\frac{\lambda \mathrm{d}^2T}{\mathrm{d}r^2}+\frac{\lambda \mathrm{d}T}{\mathrm{d}r}\,\frac{1}{r}\right)}{C_p\rho}\right) \tag{3}$$

where:

T_s =surface temperature of the sample (K),
t =time (s),
T_{ext} =oven temperature (K),
$\mathrm{d}x$ =infinitesimal height interval (m),
$\mathrm{d}r$ =infinitesimal radial interval (m),
$\mathrm{d}t$ =inifinitesimal time interval (s),
r =radial position (m),
ρ =apparent density (kg/m^3),
(I,J) =position on the internal grid system,
$\mathrm{d}T$ =infinitesimal temperature variation associated with conductive heat transfer with respect to the cylinder height and radius, respectively,

$$\mathrm{d}T=(T(I+I,J)-T_s(I,J)) \tag{4}$$

$$T=(T(I,J+1)-T_s(I,J)) \tag{5}$$

h_{tot} is the overall heat transfer coefficient expressed as:

$$h_{tot}=h+\frac{\lambda_c}{\Delta x} \tag{6}$$

where h is the convective heat transfer coefficient (W/m^2 K), λ_c is the thermal conductivity of the tin plate container (W/m K), and Δx is the container thickness (m).

C_p is the specific heat of the product (J/kg K), which varies as a function of temperature and moisture according to the following equation (Zanoni & Petronio, 1991):

$$C_p=(0{\cdot}013T^2-0{\cdot}217T+4179)X_w+(5T+1390)(1-X_w) \tag{7}$$

The following equation describes heat transfer inside the sample:

$$\frac{dT}{dt}=\alpha\left(\frac{1}{r}\frac{dT}{dr}+\frac{d^2T}{dr^2}+\frac{d^2T}{dx^2}\right) \tag{8}$$

where α is the thermal diffusivity of the sample (m^2/s). The value α is evaluated by determining the value that minimizes the mean square error between the temperature profile calculated in the geometric core of the product and the experimental temperature profile. The mean square error (MSE) is calculated by the following equation:

$$\mathrm{MSE}=\sum_1^n\frac{(V_s-V_c)^2}{n} \tag{9}$$

where

V_s =experimental temperature value (K),
V_c =calculated temperature value (K),
n =number of experimental temperature values.

An original numerical computer model in Fortran programming language was set up and a PC was used to solve the mathematical model. The above-mentioned equations were solved by the numerical explicit solution by finite differences. The boundary conditions are:

At $t=0$ $T=T_o$	for $0<r<R$ and $0<x<H/2$
At $t>0$ $T=T_s$	for $r=R$ and $0<x<H/2$
$dT/dr=0$	for $r=0$
$T=T_s$	for $x=0$ and $0<r<R$
$T=T_s$	for $x=H/2$ and $0<r<R$

where H is the height and R is radius of the sample.

Measurement of apparent density

The apparent density of crust and crumb samples was determined by using the EEC Official Method (Godon & Loisel, 1984). In this method, millet seeds are used, whose apparent density (ρ) must be determined by weighing a known volume of seeds. A crust or crumb sample with known weight (P) is put into millet seeds, and all is weighed. Since the weight of the container with the seeds is known, the total volume (V) of the sample can be evaluated by the equation:

$$V=\frac{(B-(A-P))}{\rho} \tag{10}$$

where

B =weight of the container and the seeds (g),
A =weight of the container, the seeds and the sample (g),
ρ =apparent density of millet seeds (g/ml),
P =weight of the crumb sample (g).

Since the volume is known, the apparent density of the sample is then:

$$\rho=\frac{P}{V} \tag{11}$$

Measurement of the convective heat transfer coefficient

The convective heat transfer coefficient defined in eqn (8) was evaluated experimentally in the oven following the method described in detail elsewhere (Gianotti, 1992). The measurement was carried out by using a parallelepiped-shaped, hollow, PLEXIGLAS GS (Plasti d.b., Milan, Italy) cell (height 110 mm, square cross-section 70 mm, wall thickness 12 mm). Two type J thermocouples (diameter 0·5 mm) were placed into one of the walls at a depth of 2 and 8 mm from the external surface.

In order to carry out the measurement, the cell is placed in the oven. A water stream at 16°C was used to cool the cell inside. The cooling water flow in the cell was adjusted so that inlet and outlet water temperatures coincided. The cooling water temperature was measured by type T thermocouples (diameter 2 mm), placed at the cell inlet and outlet. The air temperature in the oven was measured by type T thermocouples (diameter 2 mm). The thermocouples were connected to the data acquisition and recording system (Datascan 7720, Datagest Srl, Milan, Italy) interfaced by RS 232 to a PC.

Heat transfer through the walls was in steady state. As a result, the temperature profile in the wall thickness was linear, and values for temperatures at the internal and external surface could be obtained by extrapolation from internal experimental temperatures.

The steady state flow heat through the walls is defined by the Fourier's equation:

$$\frac{Q}{A}=\lambda\ \frac{\Delta T}{\Delta x} \tag{12}$$

where

Q/A = area heat flow (W/m^2),
λ = thermal conductivity of cell (0·19 W/m K),
ΔT = temperature difference (°C) between external and internal walls,
Δx = wall thickness (m),

since:

$$\frac{Q}{A}=h(T_a-T_p) \tag{13}$$

where

h = convective heat transfer coefficient between air and cell (W/m^2 K),
T_a = air temperature (°C),
T_p = external wall surface temperature (°C).

When values for the temperatures at the external and internal wall surface, for the air temperature, for the thermal conductivity of the cell and for the wall thickness are known, the convective heat transfer coefficient can be calculated by the following equation:

$$h=\frac{\lambda \Delta T}{\Delta x(T_a-T_p)} \tag{14}$$

Experiments were carried out under varying air and temperature conditions, and a constant value of h was obtained, which was 30 W/m^2 K.

RESULTS AND DISCUSSION

Modelling of thermophysical properties

The experimental conditions of the tests carried out to determine the thermal diffusivity of the crust and the crumb are summarized in Table 3.

Two comparisons between experimental and calculated temperature profiles are reported in Figs 1 and 2 for bread crumb at 24% porosity and bread crust at 20% porosity, respectively. It can be seen that the temperatures calculated by the mathematical model are similar to the experimental ones. Similar behaviour was observed for all the experimental tests. This suggests that the hypotheses on heat transfer inside the product and the experimental values of thermophysical properties used to solve our model are adequate.

The values for thermal diffusivity and apparent density of bread crust and crumb as a function of porosity are reported in Table 4. The analysis of the experimental data of apparent density as a function of porosity shows a linear correlation according to the following equations:

$$\text{For the crumb:} \quad \rho_{crumb}=979-9{\cdot}90\varepsilon \quad r=0{\cdot}99 \tag{15}$$

TABLE 3
Experimental Conditions of Thermal Diffusivity Tests

Characteristics	*Crumb*	*Crust*
Sample height (m)	$5{\cdot}4\times10^{-2}$	$5{\cdot}4\times10^{-2}$
Sample radius (m)	$3{\cdot}6\times10^{-2}$	$3{\cdot}6\times10^{-2}$
Initial sample temperature (°C)	24	18
Sample moisture content (%)	46·0	0·0
Oven temperature (°C)	100	100
Convective heat transfer coefficient (W/m^2 K)	30	30
Thermal conductivity of container walls (W/m K) (Hayes, 1987)	50	50
Container thickness (m)	$2{\cdot}5\times10^{-4}$	$2{\cdot}5\times10^{-4}$

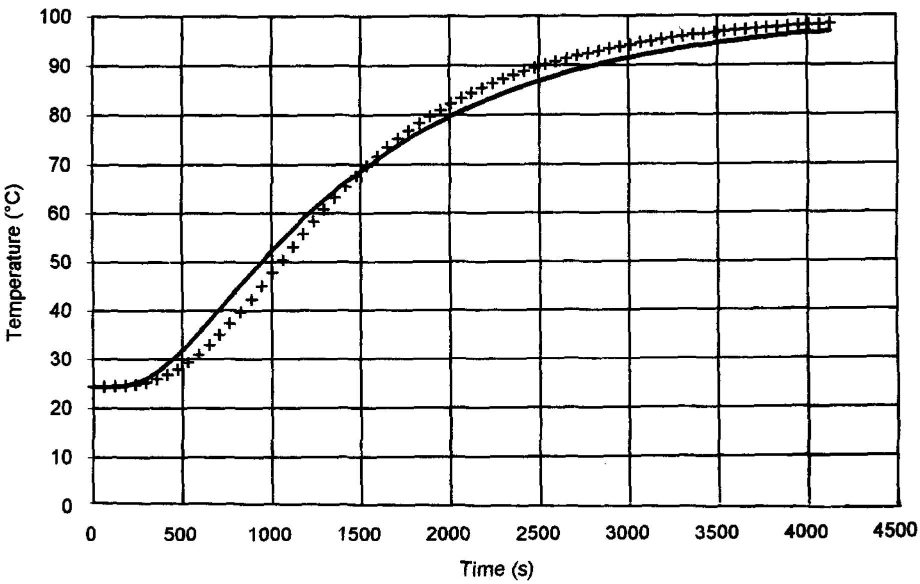

Fig. 1. Experimental (+) and calculated (----) temperature profile of bread crumb at 24% porosity.

$$\text{For the crust:} \quad \rho_{crust}=895-9{\cdot}0\varepsilon \quad r=0{\cdot}99 \tag{16}$$

where ρ is the apparent density (kg/m^3) and ε is the porosity (%).

The linear trends of the crust and the crumb are almost parallel. This confirms that, at the same porosity, the difference in density between the crust and the crumb is caused by the water content. Consequently, the following empirical model for variation in the apparent density of bread as a function of porosity and moisture can be obtained:

$$\rho_{bread}=[\rho_w x_w+\rho_d(1-x_w)]-k\varepsilon \tag{17}$$

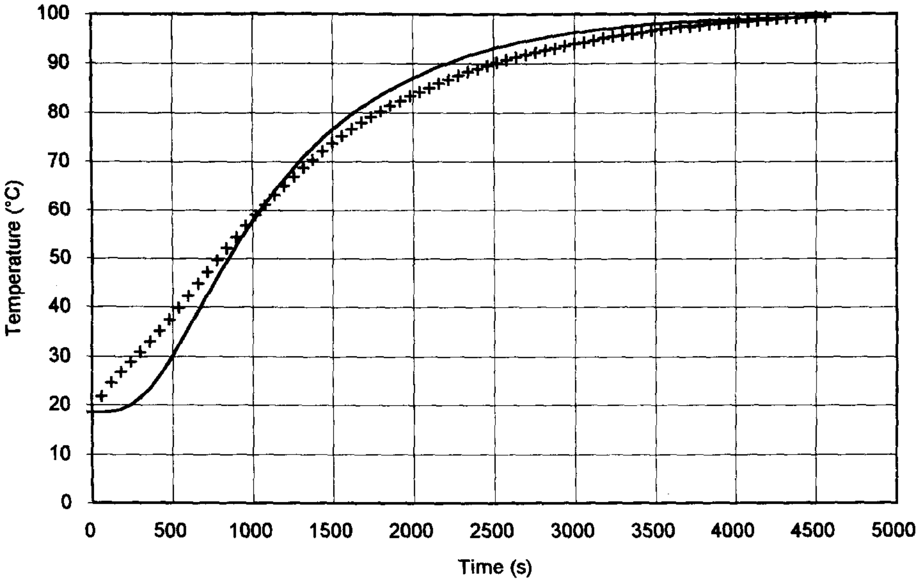

Fig. 2. Experimental (+) and calculated (----) temperature profile of bread crust at 20% porosity.

where

ρ_w =water density=1000 kg/m^3 (Miles *et al.*, 1983),
ρ_d =dry matter density=895 kg/m^3,
x_w =mass fraction of water (kg water/kg product),
ε =porosity (%),
k =9·45 (kg/m^3 %).

Experimental values for the apparent density of the crust and the crumb are in good agreement with those reported in the literature (Rask, 1989).

Values for the thermal diffusivity of both the crust and the crumb increase exponentially with porosity according to the following equations (Fig. 3):

$$\text{For the crumb:}\quad \alpha_{\text{crumb}}=\exp(0{\cdot}01\varepsilon-15{\cdot}25)\quad r=0{\cdot}99 \tag{18}$$

$$\text{For the crust:}\quad \alpha_{\text{crust}}=\exp(0{\cdot}0062\varepsilon-15{\cdot}30)\quad r=0{\cdot}96 \tag{19}$$

The difference in behaviour between the crust and the crumb is caused by the combined effect of the variation in apparent density, specific heat and thermal conductivity. The last of these follows a decreasing trend on increasing porosity; differences between the crust and the crumb are only due to the different water content. For instance, the conductivity trend of the crust and the crumb at 100°C can be described by the following equations (Table 4):

$$\text{For the crumb:}\quad \lambda_{\text{crumb}}=0{\cdot}768-5{\cdot}0\times10^{-3}\varepsilon\quad r=0{\cdot}96 \tag{20}$$

$$\text{For the crust:}\quad \lambda_{\text{crust}}=0{\cdot}398-3{\cdot}1\times10^{-3}\varepsilon\quad r=0{\cdot}99 \tag{21}$$

TABLE 4
Thermophysical Properties of Bread Crust and Crumb as a Function of Porosity

Crumb

Porosity (%)	0	24	37	50	71	79
Apparent density (kg/m^3)	974	743	610	491	283	187
Thermal diffusivity (m^2/s) $\times 10^{-8}$	25	29	33	40	50	53
Thermal conductivity[a] (W/m K)	0·729	0·645	0·602	0·588	0·423	0·297
Specific heat[b] (J/kg K)	2992	2992	2992	2992	2992	2992

[a] Calculated as $\lambda = \alpha \rho C_p$.
[b] Calculated by eqn (7).

Crust

Porosity (%)	0	20	48	71
Apparent density (kg/m^3)	895	716	462	258
Thermal diffusivity (m^2/s) $\times 10^{-8}$	23	26	28	37
Thermal conductivity[a] (W/m K)	0·389	0·352	0·244	0·180
Specific heat[b] (J/kg K)	1890	1890	1890	1890

[a] Calculated as $\lambda = \alpha \rho C_p$.
[b] Calculated by eqn (7).

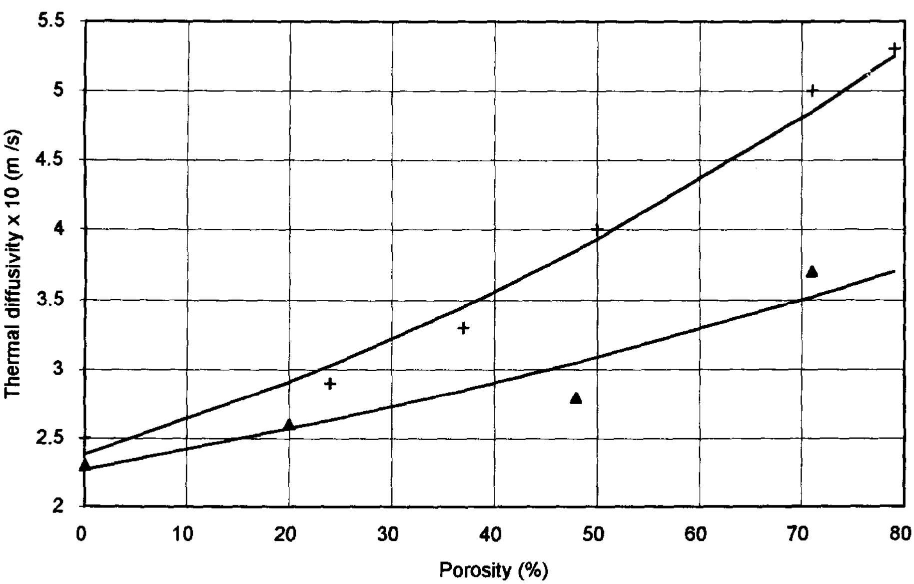

Fig. 3. Thermal diffusivity trend as a function of porosity (symbols are experimental data: + crumb; ▲ crust; lines are calculated data).

From Table 4 it can be observed that the thermal diffusivity of the crumb increases with increase in porosity. When porosity increases from 0 to 79%, the thermal diffusivity increases two-fold. Therefore, porous crumb can conduct heat more rapidly than firm crumb. This observation seems to confirm the hypothesis by De Vries *et al.* (1989) that evaporation–condensation on gas cells in the crumb results in more rapid heat transfer in porous crumb than in non-porous crumb. However, the results on the thermal diffusivity of the crust demonstrate that, in the absence of water and, therefore, of any evaporation–condensation mechanism, the thermal diffusivity increases with increase in porosity. It can be assumed that the higher rate of heat transfer in a porous product is not due to evaporation–condensation phenomena, but rather to the lower heat capacity as a result of the lower specific heat and density.

CONCLUSIONS

This research allowed some thermophysical properties, such as thermal diffusivity, apparent density and porosity of bread crust and crumb to be determined experimentally. A method was set up to determine the thermal diffusivity of bread crust and crumb. It is based on the comparison between the temperature profile obtained experimentally during heating of the sample in an oven at 100°C and the temperature profile calculated using a computer program to simulate heat transfer inside the product. A good correlation between theoretical and experimental temperature profiles was obtained, indicating that the method is accurate and reproducible.

Experimental measurements showed that the apparent density of the crust and the crumb follows a linear trend as a function of porosity and that the thermal diffusivity follows an exponential trend as a function of porosity. Experimental values for the thermal diffusivity and conductivity of the crust and the crumb are higher than those reported in the literature (Rask, 1989).

Based on the authors' data, the hypothesis by De Vries *et al.* (1989) that evaporation–condensation on gas cells in the crumb results in more rapid heat transfer in porous crumb than in non-porous crumb is refuted. In fact, the higher rate of heat transfer in a porous product is due to the lower heat capacity as a result of the lower specific heat and density.

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