Modeling the Thermal Properties of a Cup Cake During Baking

O. D. Baik, S. S. Sablani, M. Marcotte, and F. Castaigne

ABSTRACT

Thermal properties of a cup cake were estimated under conditions simulating industrial baking. Densities (ρ: 803-236 kg/m^3), specific heats (C_p: 2516-2658 J/kgK) and thermal conductivities (k: 0.1064-0.2064 W/mK) were estimated using a pycnometric/geometric cutting method, a modulated differential scanning calorimeter and a line heat source probe. C_p and k were based on internal temperatures after specific baking times. Thermal diffusivities (α: 1.02×10^{-7}-1.698×10^{-7} m/s^2) were obtained by dividing the thermal conductivities by the product of specific heats and densities. Based on thermal property data, simple empirical models were developed for further prediction.

Key Words: thermal conductivity (k), specific heat (C_p), thermal diffusivity (α), cup cake

INTRODUCTION

ACCURATE ESTIMATION OF ENERGY CONSUMPTION IN BAKING largely depends on oven operating conditions (air velocity, temperature, humidity, etc.) and on thermal properties such as thermal conductivity, heat capacity and thermal diffusivity of the product. Knowledge of thermal properties is important for mathematical modeling and computer simulation of heat and moisture transport (Rask, 1989; Sablani et al., 1998). Advanced simulation models can incorporate real physical and thermal properties of the product instead of the average values over the whole process.

Attempts have been made to improve measurement techniques (Alvarado-Gil et al., 1995; Buhri and Singh, 1993; Zhou et al., 1994) and prediction models of thermal properties of bakery products, including calculation programs such as COSTHERM (Miles et al., 1983). However, it has been suggested that for greater accuracy the thermal properties should be measured in each individual case (Rask, 1989).

Thermal properties depend mostly on composition (particularly, moisture content and volume expansion) and temperature. Heat capacity is independent of mass density (Sweat, 1986). These parameters change as baking proceeds and have a combined effect on thermal properties of bakery products. Griffith (1985) reported that the influence of baking time, moisture content and temperature on the thermal properties of corn-based tortilla dough was highly complex.

In order to predict thermal properties, the effects of moisture content, temperature and density of bakery products have been studied (Tadano, 1987; Christenson et al., 1989; etc.). However, those studies estimated the thermal properties varying only one or at most two parameters among moisture content, temperature or density. In order to change moisture content they dried the sample, and to change density, samples were pressed. However, results of those studies could not be applied in mathematical modeling of an industrial baking system because of the combined effects of the parameters.

Changes in thermal properties of bread resulting from combined effects of density and moisture content, have been reported by Unklesbay et al. (1981) and Bakshi and Yoon (1984) and for yellow cake by Sweat (1973). They determined thermal properties of the products by interrupting the baking process after certain time intervals. However, the thermal conductivity measurement was carried out at room temperature. Although their method ensured that similar values of product density and moisture content were obtained during baking, it did not take into account any effect of temperature on thermal conductivity. During baking, the temperatures inside the product reach around 100°C for bread and cake (Rask, 1989; Li and Walker, 1996). Tou et al. (1995) determined the thermal conductivity of bread by using a line heat source probe and found that its value at 100°C (0.341±0.081W/mK) was about twice that determined at room temperature (0.158 ± 0.012 W/mK). Thus, allowance should be made for effects of temperature.

The objectives of our study were (1) to estimate the thermal properties of a cup cake under conditions simulating industrial baking and (2) to develop a prediction model of thermal properties for possible use in the simulation of transport properties during the entire industrial cake baking process.

MATERIALS & METHODS

Cake batter

Cake batter was prepared using a method similar to that used in industrial batter preparation. Ingredients were: flour (100), sugar (100), cacao (20), shortening (44), egg (86.5), baking powder (7.8) and water (72.3) (weight % based on flour weight). A three-stage mixing method was used to pre-mix batter using a Hobart mixer (A-200T) with an agitator (A20B, 9809) (Hobart Canada Inc., Don Mills, ON). The batter temperature was controlled by adding cold water. To homogenize the batter and incorporate air into it, a 5.08cm Oakes continuous mixer (2MT1A, E. T. Oakes Corporation, Hauppauge, NY) was used. At that time cooling water was circulated to keep the batter at a constant temperature (~20°C).

Initial properties of prepared batters such as viscosity, pH, density, and temperature were maintained as close as possible to that of industrial batter (viscosity: 8127cps at 14s^{-1} of shear rate at 20°C, pH: 7.7, density: 803 kg/m^3, temperature: 20°C).

Simulation baking and Sampling

An electric fired reel-type oven (MT-4-8, Équipment de Boulangerie L. P. Inc. Victoriaville, QC) was used to bake the cake batter. The dimension of the reel-type oven was 2.06m × 1.37m × 2.01m (L ×W×H) with 6 trays. Electrical heating elements were positioned at the bottom of the oven. The baking molds and oil for greasing (soy bean oil mixed with vegetable shortening) were obtained from the baking industry. The cup cake mold consisted of 16 cavities of similar dimensions (bottom i.d.: 5 cm, top i.d.: 7 cm, ht: 3.5 cm). After spraying 1g of the greasing oil, 28.8g of batter was deposited in each cavity. Various trials were made with different baking temperatures to simulate industrial conditions. An oven temperature of 177 °C and baking time of 19.5 min in the electric fired reel-type oven resulted in product

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quality similar to that from industrial ovens. The effective surface heat transfer coefficient (h) was 15.2±0.94 W/m^{2}K during baking. The coefficient, which is based on bulk air temperature, was measured using an h-monitor (Enersyst development center, Ltd., Dallas, TX). The product characteristic parameters were volume change, moisture content, internal temperature profiles, color, and texture. The internal temperature profile of cake batter was measured using an SMOLE (Super Multichannel Occurrent Logger Evaluator, SMOLE Gold, Electronic Controls Design Inc., Milwaukee, OR) and K-type thermocouples. During the cake baking, samples were removed at 0, 4, 6, 13, 15 and 19.5 min. Between 6 min and 13 min, as soon as samples were removed from the oven they collapsed, thus sampling was not done during that period. Due to experimental circumstances, samples had to be stored. For the batters baked for 13, 15 and 19.5 min (solid state), after 15 min of air cooling, samples were packed in plastic film, quickly frozen, and stored at -45°C. No physical deterioration or decrease in moisture content was observed during frozen storage. For batters baked for 0, 4 and 6 min (liquid or semi-solid), the density and thermal conductivity were measured as soon as the samples were taken from the oven, since the phase change of those samples would cause changes in those properties.

Samples were cut while frozen and allowed to thaw at room temperature, enclosed in a plastic bag. Care was taken to minimize sample preparation time in order to minimize moisture loss. Three simulated baking trials were carried out on three days. In each trial, 3 or 4 samples were taken for each condition. Thus, a total of 9 to 12 measurements of moisture content, density, specific heat and thermal conductivity were made for each experimental condition.

Moisture content

Batter moisture content was measured using the vacuum oven method (AOAC, 1990). Samples were weighed into aluminum foil containers and dried for more than 6 h in a vacuum oven maintained at 105°C and 25 mm Hg internal pressure. The moisture content was calculated from the weight difference between the wet and dried samples.

Density

Density was calculated as sample weight divided by volume. To measure the density of the liquid and semi-solid types of batter (baked 0, 4 and 6 min) samples were immediately weighed in a pycnometer. The samples withdrawn at 13, 15 and 19.5 min were immediately frozen. Later, frozen samples were cut with a sharp knife into regular shapes. The sample was then weighed, and after thawing each dimension was measured to calculate volume.

Specific heat

Sample specific heats were determined using a modulated differential scanning calorimeter, (MDSC 2910, TA Instruments Inc., New Castle, DE) with a nitrogen cooling system. Temperature modulation (sinusoidal oscillation) of MDSC separates total heat flow into its reversing (specific heat related) and non-reversing (kinetic) components. Thus, specific heat values obtained by MDSC are more precise than those obtained with a conventional DSC (TA Instruments, 1995).

The solid types of sample (baked more than 13 min) were compressed between two metal plates to improve contact between the samples and the pan bottom, since specific heat is independent of mass density. Into an aluminum pan, 10–15 mg of sample was placed and the pan was hermetically sealed. A sealed empty pan was used as reference. The sample was scanned at a heating rate of 3°C/min over the temperature range (20–110°C). An 80s modulation period (single cycle) and ±1°C amplitude were used. Helium was used as purging gas (25 mL/min). The operating conditions were based on the report (TA Instrument, 1995) that the heating rate should be 5°C/min or less and the modulation period should be 60s or more under helium purging for best C_p accuracy.

Pure water generated by a Milli-Q^{TM} Water System (ZDZO-115-94, Millipore Corporation, Bedford, MA) was used for calibration by comparing the measured C_p of pure water with published data.

Thermal conductivity

Murakami and Okos (1989) reported that a line heat source probe method was suitable method for most types of food. In our study, the probe method was used to measure thermal conductivity. The probe (0.66 mm o.d.) consisted of a constantan heater wire and a chromel-constantan E-type thermocouple (Fig. 1). The constantan heating wire in the probe was connected to a power supply (6236B, Hewlett Packard (Canada) Ltd., Mississauga, ON). The power supply generated about 0.201 A of current which was then passed to the probe. The current was measured with a digital multimeter. When the current flowed through the probe, heat could be generated gradually, resulting in a temperature distribution within the cylindrical sample. Temperatures were recorded at 2s intervals using a data acquisition system (Hydra 2520, Fluke Corporation, Everett, WA) connected to a personal computer through an RS232 port (Fig. 2). The rate of temperature rise in the heater was directly related to the conductivity. Data were analyzed as temperature vs the log of time. The slope of the linear portion of each data set was used to determine thermal conductivity using the following Eq (1).

$$k = Q/4\pi\,[1n(t_2 - t_1)/T_2 - T_1] \qquad (1)$$

And the power uptake of the probe, Q, could be expressed as:

$$Q = RI^2 \qquad (2)$$

where t_1, t_2= times (s) for which probe heater was energized, T_1, T_2= temperatures (°C) of probe thermocouple at time t_1, t_2, respectively, R= overall resistance (Ω/m) of probe, I= current (A) passed to probe.

The overall resistance of the probe was determined by testing the resistance of pure glycerol at 21°C with its known thermal conductivity, and it was found to be 229.59 Ω/m. Samples were installed in a

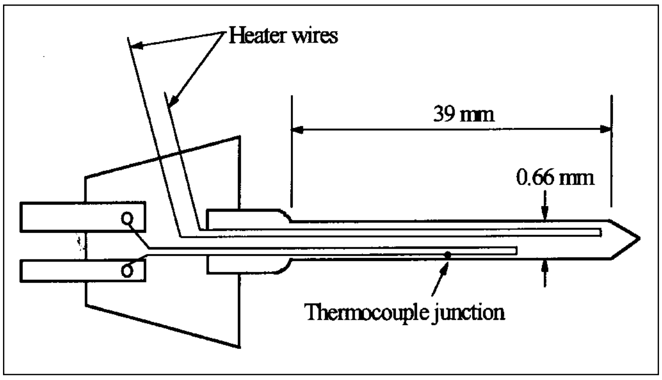

Fig 1—Simplified description of line heat source probe [adapted from Sweat (1986)].

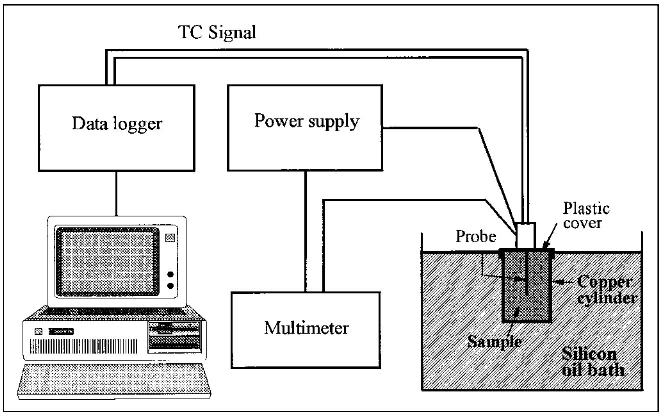

Fig. 2—Schematic of a computer based thermal conductivity measurement system.

cylindrical copper container of 4 cm i.d. and 6 cm ht.

The thermal conductivity of each sample was measured at room temperature (20±0.6°C, corresponding to 0 min baking time) and at temperatures corresponding to baking times (0, 4, 6, 13, 15 and 19.5 min). Samples baked for 4 or 6min were taken from and quickly transferred to the cylindrical copper container maintained at the temperature corresponding to the respective baking times of 4 or 6 min (54 and 68°C). For the other three conditions (13, 15 and 19.5min), initially samples taken at each baking time were quick-frozen for storage. After thawing, samples were placed in a copper container, which was then immersed in a silicon oil bath maintained at the desired temperature during measurement. During the test, the copper container was capped with a plastic cover to avoid water loss. The thermal probe was fully inserted into the sample through a small pin hole.

Thermal diffusivity

The thermal diffusivity values were calculated from experimentally measured thermal conductivity, specific heat, and bulk density of the sample, using the following equation:

$$\alpha = k \div \rho C_p \tag{3}$$

Data analysis and modeling

Statistical analysis was conducted to study the effects of temperature, moisture content, and density on thermal conductivity and specific heat using *PROC GLM* (SAS Institute, Inc., 1988). A regression model was developed for predicting the thermal properties for similar cases. The step-wise procedure was used for selecting variables to be included in the model. In order to select the best-fitting model, two criteria were considered, the correlation coefficient R^2 and the F value of the model.

RESULTS & DISCUSSION

Physical changes during baking

It has been reported that during baking, the internal temperature of bread (final moisture around 0.35, wet basis) asymptotically approaches 100°C (Rask, 1989). In the case of biscuit (final moisture around 0.03), it approaches around 130 to 210°C at 200 and 250°C oven temperatures, respectively (Fahloul et al., 1994). In our results, the internal temperature of the cup cake (final moisture around 0.28) quickly increased during baking and reached around 100°C within 13 min (Fig. 3) (error bars, Fig. 3, 4 correspond to standard deviations). The maximum cake crumb temperature reached 104°C at 19.5 min. The maximum temperature inside the product depended both on moisture content and applied oven temperatures.

Initial moisture content (m) of the batter was around 0.346 (g water / g sample), and as baking progressed it decreased linearly to 0.276 (R^2=0.964).

$$m = 0.35192 - 0.0036699t \tag{4}$$

where t= time (min), which suggests that the moisture loss from the cake followed a constant drying rate.

During baking, the batter density decreased sharply from 803 to 236 kg/m^3 from the beginning to 13 min, and then increased sharply to 281.5 kg/m^3 at 15 min. After that, it remained nearly constant (286.6 kg/m^3) to the end of baking. Sweat (1973) had reported declining density up to 75% of the baking endpoint. The density change closely followed the volumetric change. During baking, the volume increased, up to around 70% of baking time due to incorporated gases that were released. In addition, gas cell formation occurred due to CO_2 production from the chemical leavening agent reaction. Finally, the cake collapsed. Thus, the volume of cup cake batter increased to around 13 min of the baking process, then slightly decreased to the end, while the moisture content decreased steadily.

Thermal conductivity

The thermal conductivity was a function of baking time (Fig. 4). At room temperature, the thermal conductivity of the cup cake batter was 0.2064±0.0072 W/mK. This was lower than that the value estimated by Sweat (1973) for yellow cake batter (k=0.223 W/mK) with 0.415 moisture and 693.5 kg/m^3 density. Thermal conductivities measured at temperatures corresponding to 4 and 6 min baking time were 0.1871±0.0046 and 0.1957±0.0136 W/mK, respectively. The average value for thermal conductivity at 6 min was slightly higher than that at 4 min. This might have been caused by an experimental error concerning the density decrease resulting from structure collapse during sampling of semi-solid type cake batter. Thermal conductivity of batter baked for 4 and 6 min, when estimated at room temperature, was 0.2165±0.0107 and 0.2833±0.0172 W/mK, respectively. When batter baked for 4 and 6 min was cooled to room temperature, densities increased from 662.7 to 915.4 and from 557.7 to 1120.4 kg/m^3, respectively, since the leavening gases escaped from the liquid batter with time. This density change caused higher thermal conductivities in the batters when estimated at room temperature, compared to those estimated under simulated baking conditions.

For solid cakes baked for 13, 15 and 19.5 min, the thermal conductivities estimated at room temperature were 0.0703±0.00321, 0.0683±0.0046 and 0.0683±0.041 W/mK, respectively. These values were about one third that of batter at 0 min baking time. The thermal conductivities of cakes baked for 13, 15 and 19.5 min mea-

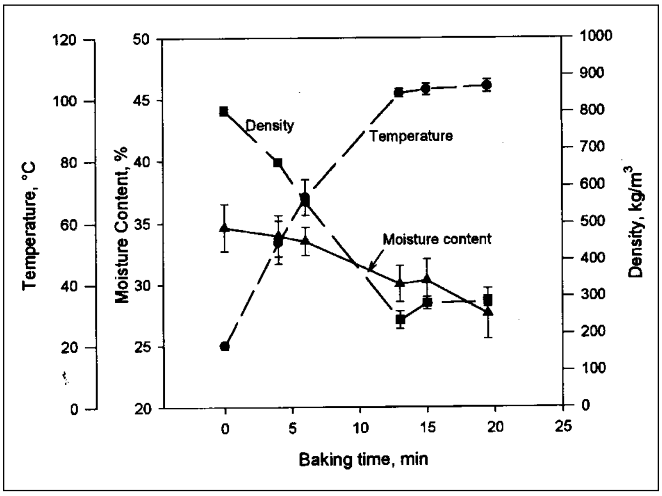

Fig. 3—Changes in physical properties of a cup cake batter during baking in an electric fired reel-type oven kept at 177°C (*h*=15.2±0.94 W/m²K), n=9-12.

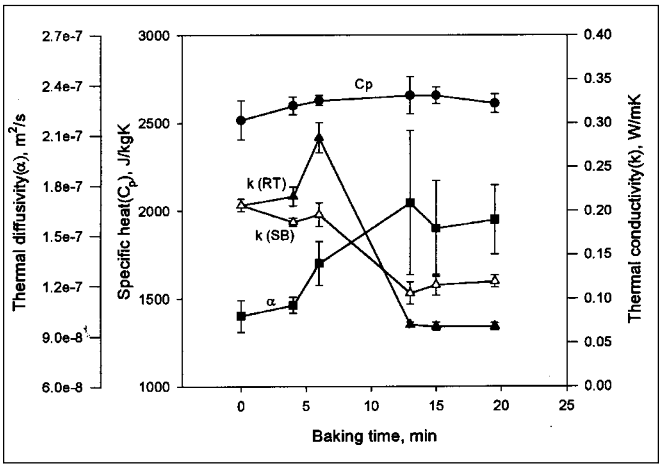

Fig. 4—Changes in thermal properties of a cup cake during baking in an electric fired reel-type oven kept at 177°C (RT: room temperature, SB: simulated baking), n=9-12.

sured at temperatures corresponding to baking time, 102, 103 and 104°C were 0.1064±0.0124, 0.1155±0.0117 and 0.1195±0.00691 W/mK, respectively. These values were about 1.7 times higher than those measured at room temperature. Two previously published models of thermal conductivity for muffin (Christenson et al., 1989) and cake (Rubio and Sweat, 1990) were applied to our experimental data. These models and MSE (mean square errors) between the values from models and experimental values were compared (Table 1). This comparison method was similar to that applied by Rubio and Sweat (1990). Mean square errors were calculated using Eq (5):

$$\mathrm{MSE} = \Sigma\,(k_{\exp i} - k_{\mathrm{mod}\, i})^2 \div \text{degree of freedom} \qquad (5)$$

where, $k_{\exp}$= experimental value of thermal conductivities (W/mK) in the present study, k_{mod}=calculated thermal conductivities (W/mK) from each model.

The model developed for a muffin (Christenson et al., 1989) did not fit our experimental data well. MSE value was 1.990 for data estimated at simulated baking temperatures and 0.034 for data estimated at room temperature. Although MSE for the data at room temperature was smaller than that for simulated temperatures, it was not satisfactory for predicting thermal properties (Table 1).

Rubio and Sweat (1990) determined the effects of moisture content ranging from 0.394 to 0.449 and density ranging from 81.0 to 276.5 kg/m^3 on thermal conductivity of bread. They found that density was the predominant parameter ($p<0.0001$). They also developed a model for three types of cakes (moisture 0.346 to 0.411 and density 0.253 to 0.529). Their model for cakes was applied to our experimental data and showed MSE of 0.00167 which is lower than that obtained with the Christenson et al. (1989) model.

Moisture content, density and temperature had effects ($p<0.0001$) on thermal conductivity of cup cake during baking). The interaction between moisture content and density also affected thermal conductivity ($p<0.002$). The prediction model for thermal conductivity was developed based on the significant variables [R^2 =0.991, F-value=1645($p<0.0001$)].

$$k = 0.00263T - 0.831m - 0.000910\rho + 0.00422m\rho \qquad (6)$$

where, k=thermal conductivity (W/mK), m=moisture content (g water/g sample), ρ=density (kg/m^3), T=temperature (°C). The mean square error of the model was 0.000105. A 3-dimensional surface plot was made (Fig. 5) of the thermal conductivity calculated from Eq 6, as a function of moisture content and density at three temperatures.

Specific heat

Specific heat of cake batter at room temperature (20 °C) was 2516.8 J/kgK. The specific heat increased to 2658 J/kgK at 13 min of baking, then decreased to 2613 J/kgK by the end of baking. Moisture content and temperature have an important influence on specific heat of bakery products. The specific heat increases with rising temperature and decreases with falling moisture. During baking, the internal temperature of the product increased, but moisture content decreased; thus, the resulting product C_p increased only slightly. After 13 min of baking the temperature of the product remained nearly constant, but the moisture content decreased continuously. As a result, a small decrease in specific heat of cake occurred. A traditional mass fraction model (Polak, 1984) was applied to our experimental data, but it did not fit our experimental data well (mean square error: 17869).

Using *PROC GLM* (SAS Institute, Inc., 1988), a model for specific heat was developed as a function of moisture content and temperature [R^2=0.999, F-value=24436 ($p<0.0001$)].

$$C_p = 7107m + 18.7T - 45.3mT \qquad (7)$$

The mean square error in the model (8.2505) was much lower than that of the traditional mass fraction model (Table 2). A 3-dimensional surface plot was made (Fig. 6) of the specific heat estimated using the developed model. Moisture content and temperature had effects ($p<0.0001$) on the specific heat of a cup cake during simulated industrial baking. Interaction between the two variables was significant as well ($p<0.0001$).

Table 1—Thermal conductivity models and mean square error values for experimental data

References	Equation[a]	MSE
Christenson et al. (1989)	$\ln k = -48.0 - 10.9\,m + 0.272T' + 0.053\,mT'$ $-4.1 \times 10^{-4} T'^2$ $(293K < T < 358K;\ 0 < m < 0.6)$	1.990 ($T' > 20°K$) 0.034 ($T' = 20°K$)
Rubio and Sweat (1990)	$k = 0.0844 + 0.0892\,\rho'$ $(0.346 < m < 0.411;\ 0.2529 < \rho' < 0.5290)$	0.00167
Present study	$k = 0.00263T - 0.831m - 0.000910\rho + 0.00422m\rho$	0.000105

[a] T' is in Kelvin; ρ' is in cm^3

Table 2—Specific heat models and mean square error values applied to experimental data

Reference	Equation	MSE
Mass fraction model (Polak, 1984)	$C_p = (1\text{-}m)\,C_{psol} + mC_{pw}$	17869.1
Present study	$C_p = 7107m + 18.7T - 45.3mT$	8.2505

Thermal diffusivity

For conduction heat transfer in food, the temperature-time relationship may be calculated if the heat transfer boundary conditions and the food geometry are mathematically traceable and if the thermal diffusivity is known. Precise knowledge of thermal diffusivity of a cup cake during baking is essential in the mathematical simulation of heat and mass transfer during process.

Changes in thermal diffusivity (α) of the cake were due to changes in density, thermal conductivity and specific heat. The thermal diffusivity of batter at room temperature and 0 min baking time was 1.02×10^{-7} m^2/s. This was close to that (1.09×10^{-7} m^2/s) reported for yellow cake batter (Sweat, 1973), and it was also in the range of values ($0.8\text{-}1.2\times10^{-7}$ m^2/s) reported for biscuit dough (Kulachi and Kennedy, 1978). Additionally, the estimated value of α was lower than that reported for bread dough 1 to11.8$\times10^{-7}$ m^2/s (Sluimer and

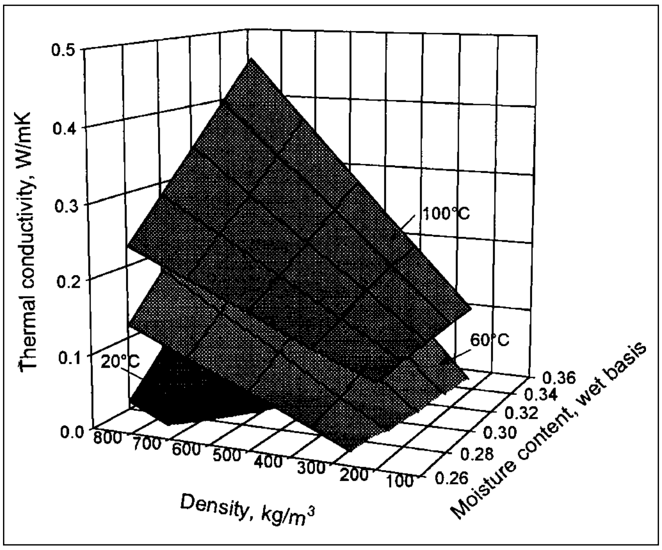

Fig. 5—Thermal conductivity calculated from a simple empirical model (Eq 6), as a function of density and moisture at three temperatures.

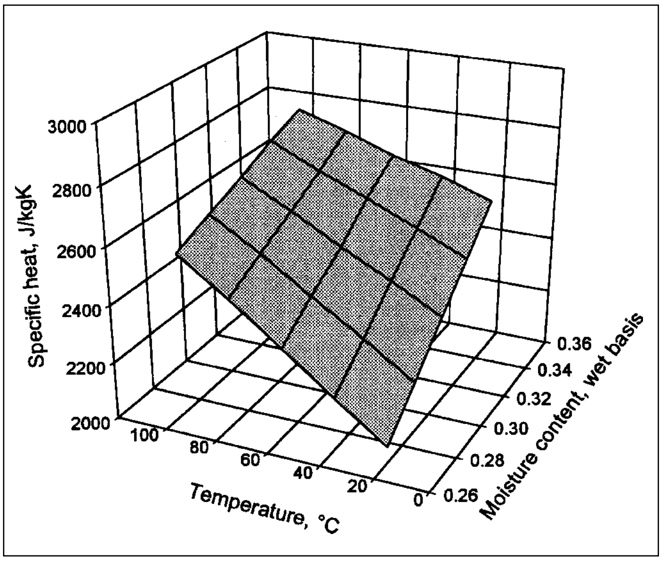

Fig. 6—Specific heat calculated from a simple empirical model (Eq 7), as a function of temperature and moisture content.

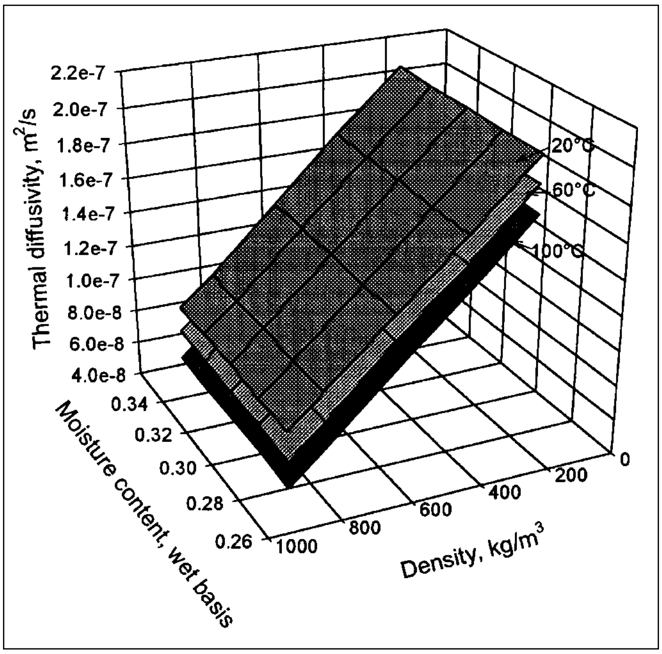

Fig. 7—Thermal diffusivity calculated from a simple empirical model (Eq 8), as a function of density and moisture at three temperatures.

Krist-Spit, 1987; Tou et al., 1995) and muffin 5.7×10^{-7} m²/s (Tou and Tadano, 1991). In our results, thermal diffusivity increased to 1.5958×10^{-7} m²/s by the end of baking with a maximum of 1.698×10^{-7} m²/s after 13 min baking. Similar changes had been reported by Sweat (1973). A prediction model of thermal diffusivity during simulated baking was developed as a function of density, temperature and moisture ($R^2 = 0.971$)

$$\alpha = 2.55\times10^{-8}m - 1.75\times10^{-10}\rho - 3.95\times10^{-10}T + 2.42\times10^{-7} \quad (8)$$

A 3-dimensional surface plot of thermal diffusivity was made (Fig. 7) based on Eq 8. The effect of density was greater than that of moisture content. In the moisture range of 0.27 to 0.35 thermal diffusivity varied from 2.061×10^{-7} to 2.082×10^{-7}m²/s, and in the density range of 200 to 800 kg/m³, thermal diffusivity varied from 2.061×10^{-7} to 1.01×10^{-7} at 20°C. An increase in moisture content and density of 1% caused 0.033% increase and 0.172% decrease, respectively, in thermal diffusivity during baking.

CONCLUSIONS

THERMAL PROPERTIES (CONDUCTIVITY, SPECIFIC HEAT AND DIFfusivity) of a cup cake during baking were determined. Estimated values reflected the combined effects of moisture content, temperature and density of the product on thermal properties. The effects of the interactions between moisture content and density on thermal conductivity were significant, and as well the effects of interactions between temperature and moisture content on specific heat. Simple empirical models were developed for thermal conductivity, specific heat and thermal diffusivity. These models were based on thermal properties measured under conditions similar to real baking. They would be useful in the mathematical simulation of heat and mass transfer in cup cakes during industrial baking.

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