Effect of Temperature and Composition on Thermal Conductivity of "Mlinci" Dough

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Abstract

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The objective of this study was to determine the thermal conductivity of "Mlinci" dough T-500 and "Mlinci" dough T-500 with the addition of eggs, wheat germs and wheat bran in the temperature range of 40°C to 70°C. Thermal conductivity was determined using modifications of guarded hot plate steady state method. For all types of dough, thermal conductivity first increased with temperature and then, after reaching maximum values, it decreased. The maximum values for "Mlinci" dough T-500 containing wheat germs and bran were 54°C, and for "Mlinci" dough T-500 with eggs were 58°C. The minimal value of 0.347 ± 0.020 W/mK was determined for "Mlinci" dough T-500 at 39.38°C. The maximum value 0.585 ± 0.023 W/mK was determined for "Mlinci" dough T-500 with wheat bran at 54.39°C. The thermal conductivity of "Mlinci" dough T-500 with the addition of wheat germs and wheat bran was higher in comparison with the basic composition due to the elevated amounts of ash, water, proteins, and porosity, as well as non-homogeneity. Based on the experimental thermal conductivity values of "Mlinci" dough T-500 samples at various temperatures, quadratic polynomial equations were developed. The research results could be used for the modelling of the heat transfer of "Mlinci" dough T-500 during processing.

Keywords: steady state method; thermal properties of dough

Croatian unleavened flat bread "Mlinci" is a type of flat bread produced from wheat flour, water and salt. Due to the new trends for healthy products, in this study the basic "Mlinci" dough T-500 was enriched by adding egg, wheat germs and wheat bran for the improvement of the nutritive and sensory quality of the product.

Dough is prepared as for chapati (Indian flat bread) and baked on a hot plate for a few minutes. Baked "Mlinci" can be stored for several months. "Mlinci" are different from chapati, and their final treatment includes cooking in water for approximately 1–2 min. "Mlinci" are a traditional Croatian dish, consumed as a side dish with baked turkey.

To design a continuous baking and puffing oven for "Mlinci", it is necessary to know the energy requirement in the system. The thermal conductivity of dough is an important physical property needed in the analysis of the heat transfer during the processing. The thermal conductivity data can be predicted using mathematical models and ex-

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perimental determinations. For the determination of thermal conductivity, either transient or steady state heat transfer methods are used depending upon the nature of the material.

Up to now, many researchers have measured the thermal properties of foods applying various measurement techniques that can be found in the literature. Some comprehensive reviews have also been published. However, the information regarding the thermo-physical properties of dough and bakery products during baking is scarce when compared with other products.

Choi and Okos (1985) established the general mathematical models to predict the thermal properties of food products. It was developed on the basis of the thermal properties of each pure component and its weight fraction that was an easily measurable factor compared to the volume fraction. These mathematical models were established for the temperature range of –40°C to 150°C. Califano and Calvelo (1991) calculated the thermal conductivity of potato on the basis of the heat penetration into cylindrical samples between 50 and 100°C. They found that thermal conductivity varied with temperature in a quadratic polynomial form. Willix *et al*. (1998) reported thermal conductivity as a function of temperature for 27 foods in the temperature range of –40°C to +40°C determined by a guarded hot plate apparatus. An artificial neural network (ANN) approach was used to model the thermal conductivity of bakery products as a function of the product moisture content, temperature, and apparent density (Sablani *et al*. 2002). The model developed was capable of predicting the thermal conductivity values of various bakery products for a wide range of conditions with the mean relative error of 10%, and the mean absolute error less than 0.02 W/mK. Kulacki and Kennedy (1978) reported the results of an experimental study on the thermal conductivity of two different types of standard dough: AACC and hard-sweet formula. In the present experiments, a single plate thermal conductivity apparatus was used. Thermal conductivity was determined in the temperature interval of 24.35°C to 64.15°C. Griffith (1985) determined the thermal conductivity of a reconstituted corn-based tortilla dough using the temperature history method. The author calculated thermal conductivity from the slope of the time-temperature curve and the temperature difference between the center and the surface. Moreira *et al.* (1995) gave very useful experimental tips for the thermal conductivity measurement of thin products (tortilla chips) using a line heat source probe. Gupta (1993) used the guarded hot plate steady state method with a slight modification to suite the shape and size of rolled or baked chapati. The thermal conductivity of the test materials was measured at 35, 44, 53.3, and 62.5°C. Based on the experimental thermal conductivity values of wheat flour dough and baked chapati, the author developed equations for the moisture range of 35% to 50%, temperatures 30°C to 60°C, and density of 1000–1200 kg/m^3. Baik *et al.* (2001) discussed both the common and the new measurement techniques, prediction models, and published data on thermo-physical properties of bakery products: specific heat, thermal conductivity, thermal diffusivity, and density.

Table 1. The composition of "Mlinci" dough T-500 and "Mlinci" dough T-500 with different addition of wheat germs, wheat bran and egg

Ingredient	Weight (kg)			
	T-500	T-500 + eggs	T-500 + wheat germ	T-500 + wheat bran
Flour T-500	1	1	0.8	0.8
Wheat germ	–	–	0.2	–
Wheat bran	–	–	–	0.2
Eggs	–	0.12	–	–
Salt	0.0053	0.0053	0.0053	0.0053
Antischim	0.0053	0.0053	0.0053	0.0053
Vinegar	0.0134	0.0134	0.0134	0.0134
Water	0.46	0.37	0.45	0.54
Total	1.5	1.54	1.45	1.56

The objective of this study was to determine the thermal conductivity of basic "Mlinci" dough T-500 and "Mlinci" dough T-500 with different additions, and to find the relationship between thermal conductivity, temperature and composition.

MATERIALS AND METHODS

Materials. The measurements of thermal conductivity were performed with the basic "Mlinci" dough T-500 and with the "Mlinci" dough T-500 with the addition of fresh eggs, wheat germs and wheat bran. The amount of flour in the basic composition of "Mlinci" dough T-500 was substituted by 20% wheat germs and bran (Table 1).

"Mlinci" dough T-500 samples were prepared in the industrial laboratory Đakovština Food industry and cereals trade P.C. Tena, Đakovo, Croatia. The samples of "Mlinci" dough T-500 were prepared by mixing flour T-500 with water and kneading the mixture in a low batch mixer for 15 min. After resting of 15–20 min, the dough was divided, rounded and flattened in the rolling machine (Roll-fix) to a flat round cake with a thickness of 3 mm and diameter of 111.5 mm.

Methods. The composition of the test materials was analysed using ICC standard analytical methods. The ICC standard No. 104/1 was used for the determination of ash, and standard No.110/1 for the determination of moisture. The composition of the stabilised wheat germs, wheat bran, and flour was determined in the analytical laboratory Đakovština Food industry and cereals trade P.C. Tena, Đakovo, Croatia (Table 2).

The density of dough was determined by weighing a known volume of the dough. The contents of protein and starch were calculated according to the above mentioned data (Table 3).

Thermal conductivity was determined by means of the apparatus TC-1 that represents a modification of the guarded hot plate steady state method as described in ASTM Standard C 177-76 (Anonym 1976) for dough. This is a single-plate thermal conductivity apparatus with the adaptability to different test specimen thickness (3–10 mm) and various homogeneous food materials. The tem-

Table 2. Composition of stabilised wheat germs, wheat bran, flour T-500 and fresh egg

Ingredient	Wt (% db.)			
	stabilised wheat germ	wheat bran	flour T-500	fresh egg
Water	4	5	13.68	73.6
Ash	6	–	0.46	0.8
Protein	29	23	11.00	12.8
Fat	9.5	–	1.10	11.8
Invert sugar	14	–	–	–
Cellulose	3.5	–	–	–
Starch	28	15	–	–
Diet fiber	–	35	0.10	–
Carbohydrate	–	–	73.56	1.0

Table 3. Determined values for water, ash, protein, carbohydrate and density for "Mlinci" dough T-500 samples

Samples	Constituent (%)				
	water	ash	protein	carbohydrate	density (kg/m^3)
"Mlinci" T-500	30.00	0.700	7.41	48.93	1076
"Mlinci" T-500 + eggs	24.03	0.939	7.77	48.31	1087
"Mlinci" T-500 + wheat germ	30.82	1.843	10.10	46.15	1013
"Mlinci" T-500 + wheat bran	34.62	2.015	10.14	46.66	1063

perature was measured with Pt 100 thermocouples. The apparatus and measurements system for on-line data, the software for the control of the process, and the statistical evaluation of thermal conductivity were constructed and/or developed at the Faculty of Food Technology and Faculty of Electrical Engineering University J. J.Strossmayer of Osijek, Croatia.

Experimental procedure and calculation. The test specimen whose composition and density have been determined previously is placed between the heated and the cooled plates and the steady state heat flux and temperature difference across the specimen are measured. After a certain period of time, depending on the characteristics of the material, the temperatures of the heated and cooled surfaces of the material and the final temperature of water for the accumulation of energy become constant, indicating that the steady state has been reached. All results of the measurements are stored in the computer and used in the calculations of thermal conductivity. The experiments are repeated at least five times.

According to Fourier's law of unidirectional conduction steady state rate heat flow through the material:

$$q = k \times A \times \Delta T/\Delta x \qquad (1)$$

where: q – steady state rate of heat flow through the material

The heat transferred through the material heats the water in time Δt. Thus, total heat is:

$$Q = W \times c_p (T_f - T_i) \text{ or}$$
$$Q/\Delta t = q = W \times c_p (T_f - T_i)/\Delta t \qquad (2)$$

Equating (1) and (2), ignoring the heat loss at the steady state and rearranging:

$$k = W \times c_p(T_f - T_i)\, \Delta x/A \times \Delta T \times \Delta t \qquad (3)$$

where: k – thermal conductivity (W/m K)
W – mass of water for the accumulation of energy (kg)
c_p – specific thermal capacity (J/kg K)
T_f – final temperature of water for the accumulation of energy (K)
T_i – initial temperature of water for the accumulation of energy (K)
Δx – thickness (m)
A – area surface (m^2)
ΔT – temperature difference between the heated and the cooled surfaces (K)
Δt – time for reaching the steady state (s)

For the data analysis, the Standard Practice for Statistical Treatment of Thermoanalytical Data (Anonym 2000) was used.

RESULTS AND DISCUSSION

The thermal conductivity of "Mlinci" dough T-500 samples determined by the present method are reported in Table 4 and graphically presented in Figure 1. In Figure 1, it can be seen that for all types of "Mlinci" dough T-500 samples in the temperature range of 40 to 70°C, thermal conductivity first increased with temperature up to 50°C, then it slightly increased to maximum values at 54°C for "Mlinci" dough T-500 with wheat germs and bran. The maximum values of thermal conductivity for

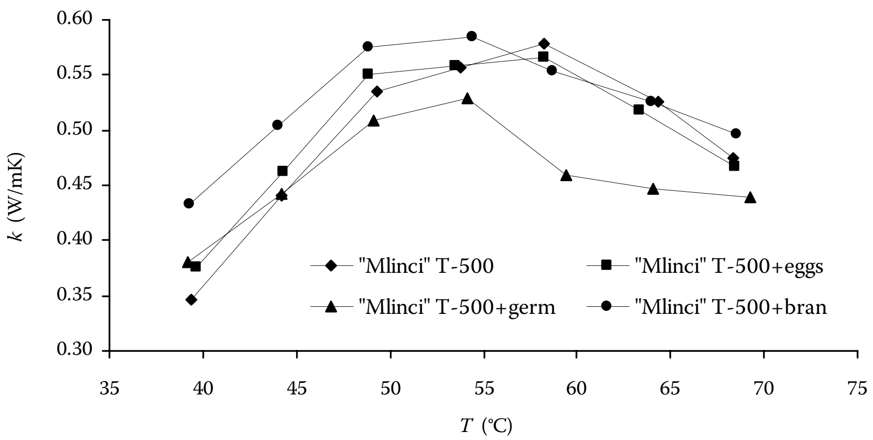

Figure 1. Variation of thermal conductivity with respect to temperature for "Mlinci" dough T-500 and "Mlinci" dough T-500 with addition of eggs, wheat germs, wheat bran

Table 4. Determined values of thermal conductivity of "Mlinci" dough T-500 samples at different temperature with values for standard deviation, pooled standard deviation and pooled relative standard deviation

Samples	Temperature (°C)	Thermal conductivity (W/m K)	Standard deviation (W/m K)	Relative standard deviation (%)	Pooled standard deviation (W/m K)	Pooled relative standard deviation (%)
"Mlinci" T-500	39.38	0.347	± 0.020	± 5.764	± 0.027	± 5.241
	44.21	0.441	± 0.022	± 4.989		
	49.35	0.535	± 0.023	± 4.299		
	53.81	0.556	± 0.020	± 3.597		
	58.24	0.578	± 0.051	± 8.824		
	64.35	0.526	± 0.012	± 2.281		
	68.38	0.475	± 0.019	± 4.000		
"Mlinci" T-500 + eggs	39.64	0.375	± 0.049	± 13.067	± 0.041	± 8.526
	44.25	0.463	± 0.015	± 3.239		
	48.83	0.551	± 0.031	± 5.626		
	53.51	0.558	± 0.043	± 7.706		
	58.20	0.566	± 0.052	± 9.187		
	63.36	0.518	± 0.030	± 5.792		
	68.46	0.467	± 0.045	± 9.636		
"Mlinci" T-500 + wheat germ	39.18	0.380	± 0.020	± 5.263	± 0.034	± 6.921
	44.17	0.443	± 0.018	± 4.063		
	49.12	0.508	± 0.046	± 9.055		
	54.16	0.529	± 0.041	± 7.750		
	59.40	0.459	± 0.043	± 9.368		
	64.10	0.447	± 0.028	± 6.264		
	69.28	0.439	± 0.024	± 4.467		
"Mlinci" T-500 + wheat bran	39.30	0.433	± 0.025	± 5.774	± 0.034	± 6.356
	43.98	0.504	± 0.036	± 7.143		
	48.82	0.576	± 0.061	± 10.590		
	54.39	0.585	± 0.023	± 3.932		
	58.65	0.554	± 0.025	± 4.513		
	63.94	0.525	± 0.011	± 2.095		
	68.53	0.497	± 0.031	± 6.237		

"Mlinci" dough T-500 and "Mlinci" dough T-500 with eggs were at 58°C. Thermal conductivity decreased after reaching maximum values.

Minimal value of thermal conductivity of 0.347 ± 0.020 W/mK was determined with "Mlinci" dough T-500 at 39.38°C, and maximal value of 0.585 ± 0.043 W/mK was determined with "Mlinci" dough T-500 with wheat bran at 54.39°C.

The data in Figure 1 indicate a reasonable trend for the temperature dependence of thermal conductivity. That kind of trend of AACC, hard-sweet dough, and chapatti was also reported in the literature. The thermal conductivity values of dough and chapati increased with temperature below 60°C but decreased above 60°C (Kulacki & Kennedy 1978; Gupta 1993). The author attributed this

Table 5. Parameters for equations type ($k = a + bt + ct^2$) for determined thermal conductivity of "Mlinci" dough T-500 samples for temperature ranges from 40 to 70°C

Samples	Temperature range (°C)	Parameters			R^2
		a (W/m K)	b (W/m K)	c (W/m K)	
"Mlinci" T-500	40–70	1.8208	0.084	–0.0007	0.9919
"Mlinci" T-500 + eggs	40–70	–1.668	0.0798	–0.0007	0.9762
"Mlinci" T-500 + wheat germ	40–70	–0.8346	0.0483	–0.0004	0.7495
"Mlinci" T-500 + wheat bran	40–70	1.0827	0.06	–0.0005	0.9273

t – temperature in °C

phenomenon to physico-chemical changes that take place above 60°C. The dough constituents react on heating to give rise to intermolecular and intramolecular cleavages which produce highly crosslinked macromolecular structures. Due to these changes, swelling and softening of starch and denaturation of protein occur, which reduces the ability of dough to conduct heat (Fessas & Schiraldi 2000).

Denaturation can be induced both by temperature and by denaturants (chemical denaturation). Above medium water content (> 5%) and above temperatures of ca. 75°C denaturation occurs. The denaturation temperature of proteins may differ due to the protein source, to the additives and the processing methods. According to De Graaf (2000), the denaturation temperature of proteins strongly depends on the water content up to its content of ≈ 10–20%. Generally the denaturation temperature of proteins decreases from 120°C to 200°C down to 80°C between 0% and 20% (w/w) water.

With the increasing water content, a steady decrease in the denaturation temperature and an increase of the denaturation enthalpy in wheat glutenins were observed. For the water content from 26.2% to 36.0%, the temperature of denaturation ranged from 50.2 to 45.5°C (Leon *et al.* 2003).

According to the above data the temperature of denaturation can significantly decrease in the case of "Mlinci" dough T-500 and "Mlinci" dough T-500 containing the additions where the moisture of the raw material was between 24.03–34.62% (Table 3). The temperature observed was 58°C for "Mlinci" dough T-500 and "Mlinci" dough T-500 with eggs, and 54°C for "Mlinci" dough T-500 with wheat germs and bran with which the change takes place (Table 4 and Figure 1).

According to the literature references, the above-mentioned temperatures correspond to the temperature of gelatinisation of wheat starch (56–62°C); it can be concluded, consequently, that swelling and softening of dough, as well as the decrease in k values, are actually the result of gelatinisation. This, however, was not confirmed experimentally, since it was not the subject of this investigation.

The experimental values of "Mlinci" dough T-500 samples were compared with an additional equation which is based on the water, protein, carbohydrate, fat, fibres, and ash contents as a function of temperature in Choi and Okos (1985). Maximum deviations were 12.99%, 22.43% and 27.68%, respectively, at 40°C, 50°C and 60°C. The deviation increased with increasing temperature. Several authors reported significant disagreement between the calculated and the measured values (Gupta 1993; Baik 2001).

Based on the experimental thermal conductivity values of "Mlinci" dough T-500 samples at various temperatures, polynomial ($k = a + bt + ct^2$) equations were developed for the temperature range from 40°C to 70°C and density from 1013 kg/m^3 to 1087 kg/m^3. The parameters and coefficients of correlation (R^2) for the equation can be seen in Table 5. The coefficients of correlation for polynomial equation were 0.75 to 0.99.

CONCLUSIONS

From the results of measurement it can be concluded that the thermal conductivity of "Mlinci" dough T-500 and "Mlinci" dough T-500 with additions depends on the temperature and composition. The thermal conductivity values of "Mlinci" dough T-500 in the temperature range of interest in this study were lower than the thermal conductivity values for "Mlinci" dough T-500 with the additions of eggs, wheat germs and wheat bran. This can be explained by the elevated amount of ash. Due to the amounts of proteins, starch and water in "Mlinci" dough T-500 samples, the maximum values of thermal conductivity were at temperature 58°C for "Mlinci" dough T-500 and "Mlinci" dough T-500 with eggs, and at 54°C for "Mlinci" dough T-500 with wheat germs and bran.

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