Individual Heat Transfer Modes During Baking of "Mlinci" Dough

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Summary

During baking of "Mlinci" dough in a batch oven heat was transferred by conduction and convection. Heat transfer by radiation in this case can be neglected due to oven design. The major portion of heat transfer was by conduction (96.09%) and minor portion by convection (3.91%). Different thermal parameters, e.g., specific heat, thermal conductivity and thermal diffusivity of „Mlinci" dough were determined. Individual mathematical models for each type of heat transfer were proposed. They were obtained by average values of thermal parameters; for thermal conductivity 0.494 W/m °C, for specific heat 2.257 kJ/kg °C for thermal diffusivity $2.034 \cdot 10^{-7}$ m^2/s, for density 1076 kg/m^3 and for free convection heat transfer coefficient 9.756 W/m^2 °C. Since the major portion of heat during baking of "Mlinci" dough in batch oven was transferred by conduction therefore the amount of heat supplied to the product can be controlled by individual models for conduction.

Key words

conduction, free convection, thermal properties, baking, "Mlinci" dough

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Introduction

Croatian unleavened flat bread “Mlinci” is a type of flat bread produced from wheat flour, water and salt. 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” is 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, specific heat and thermal diffusivity of dough are important physical properties needed in the analysis of the heat transfer during the processing. Thermal conductivity of food is an important property used in calculations involving rate of heat transfer. In quantitative terms, this property gives the amount of heat that will be conducted per unit of time through the unit of thickness of the material if a unit temperature gradient exists across that thickness. Specific heat is a quantity of heat that is gained or lost by unit mass of product to accomplish a unit change in temperature, without a change in state. Specific heat is an essential part of the thermal analysis of food processing or of the equipment used in heating or cooling of foods. In designing food processes and processing equipment, we need numerical values for the specific heat of the food and materials to be used. Thermal diffusivity is a ratio involving thermal conductivity, density, and specific heat. There are two ways to obtain such values. Published data are available that provide values of thermal conductivity and specific heat for some food and non-food materials. Another way to obtain those values is to use a predictive equation. Predictive equations are empirical expressions, obtained by fitting experimental data into mathematical models.

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 from 40°C to 150°C. Kulacki and Kennedy (1978) reported the results of an experimental study on the thermal conductivity, specific heat, density and thermal diffusivity of two different types of standard dough: AACC and hard-sweet (HS) formula. In the present experiments, a single plate thermal conductivity apparatus was used. Thermal conductivity was determined in the temperature interval from 24.35°C to 64.15°C. The specific heat measurement was based on the method of mixture in temperature range from 29.65 °C to 38.85 °C. The density of both dough types was determined by weighing a known volume of dough. All of the density determinations were made at 25°C. The thermal diffusivity of dough types was evaluated using the thermal conductivity and specific heat data presented in the paper. In the work of Hwang and Hayakawa (1979) the instrument for determination of the specific heat of cookies, wheat flour and fresh produce was described. Gupta (1990, 1993) determined the specific heat and thermal conductivity of Indian unleavened flat bread (chapatti). El-Bushra (2001) presented the construction of an isoperbol calorimeter to measure the specific heat capacity of foods. The instrument was tested with five dough types. 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.

The aim of the work reported in this paper was to determine the individual heat transfer modes during contact baking of “Mlinci” dough in batch oven. These heat transfer modes will be useful for determination of heat requirement for designing the continuous oven. Calculation of these heat transfer modes are given in Appendix A. The transfer of heat in the oven by each individual mode can be expressed in terms of temperature driving force, transfer area and heat transfer coefficient, assuming steady state heat transfer.

Material and methods

The measurements were performed with the basic “Mlinci” dough T-500 (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 cake with a length of 245 mm, width 140 mm and a thickness of 1 mm.

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 specimen thickness (3–10 mm) and various homogeneous food materials. The temperature was measured with Pt 100 thermocouples. The apparatus

Table 1. The composition of "Mlinci" dough T-500

Ingredient	Weight (kg)
Flour T-500	1
Salt	0.0053
Antischim	0.0053
Vinegar	0.0134
Water	0.46
Total	1.5

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

The sample the density of which has been determined previously, was placed between the heated and the cooled plates and the steady state heat flux and temperature difference across the sample were measured. After a certain period of time, depending on the characteristics of the sample, the temperatures of the heated and cooled surfaces of the sample and the final water temperature for the accumulation of energy became constant, indicating that the steady state was reached. All results of the measurements were stored in the computer and used in the calculations of thermal conductivity. The experiments were repeated at least five times. According to Fourier's law of undirectional conduction steady state rate heat flow trought the sample is:

$$q = \frac{k \cdot A \cdot \Delta T}{\Delta x} \quad [W] \quad (1)$$

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

$$Q = W \cdot C_p \cdot (T_f - T_i) \quad [J]$$

or

$$\frac{Q}{\Delta t} = q = \frac{W \cdot C_p \cdot (T_f - T_i)}{\Delta t} \quad [W] \quad (2)$$

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

$$k = \frac{W \cdot C_p \cdot (T_f - T_i) \cdot \Delta x}{A \cdot \Delta T \cdot \Delta t} \quad [W/m\ °C] \quad (3)$$

Where is

k Thermal conductivity of sample (W/m °C)
W Mass of water for the accumulation of energy (kg)
C_p Specific thermal capacity of water (J/kg °C)
T_f Final temperature of water for the accumulation of energy (°C)
T_i Initial temperature of water for the accumulation of energy (°C)
Δx Thickness of sample (m)
A Area surface of sample (m^2)
ΔT Temperature difference between the heated and the cooled surfaces (°C)
Δt Time for reaching the steady state (s)

The specific heat of "Mlinci" dough was determined by a modified method of mixture. It is referred to as modified because there was no direct contact between sample ("Mlinci" dough) and heat exchange medium (water). The method consisted of filling the sample in the polyethylene pouch and immersing it in the water at a different temperature. During the experiment a shaker rotated the calorimeter. The copper-constantan thermocouple types T diameter 0.025 cm (Cole-Parmer, International, U.S.A.) was used to record temperature. Data from the four thermocouples were recorded every minute with data acquisition software and hardware, PicoLog Recorder and PicoLog Player, interfered to PC at 80 MHz. The apparatus and measurements system for on-line data, the software for the control of the process, and the statistical evaluation of specific heat were constructed and/or developed at the Faculty of Food Technology and Faculty of Electrical Engineering, University J. J.Strossmayer of Osijek, Croatia.

The heat capacity of the calorimeter, H_k, that was defined as the heat required for raising the temperature of a calorimeter by 1 °C, was needed as a correction factor for specific heat determination of sample. The H_k was determined as follows:

$$H_k = \frac{C_{pw} \cdot M_w \cdot \left[T_e - T_{iw} - \left(\frac{dT}{dt} \right) \cdot t_e \right]}{T_{ik} - T_e + \left(\frac{dT}{dt} \right) \cdot t_e} \quad [J/°C] \quad (4)$$

Where is

H_k Heat capacity of calorimeter (J/°C)
C_{pw} Specific heat capacity of water (J/kg °C)
M_w Mass of water (kg)
T_e Temperature of equilibrium state (°C)
T_{iw} Water temperature at initial state (°C)
T_{ik} Temperature of calorimeter in initial state (°C)
t_e Time of equilibrium state (min)

The term $\left(\frac{dT}{dt} \right)$ was calculated from the slope from the plot temperature vs. time for calorimeter experimental data. After a certain time (20-30 min) which depends upon the characteristic of the material, equilibrium temperature was reached i.e., the temperatures of water inside the beaker, between the beaker and insulation and inside the polyethylene pouch became equal. This time represents the time of equilibrium state, t_e, which was determined experimentally. From these data heat capacity of the calorimeter was calculated.

From the law of energy conservation, i.e., the total heat in the beginning of the system is equal to the final heat of the system plus the heat lost to the environment, the following equation can be derived:

$$C_{ps} = \frac{B \cdot (T_{fw} - T_{iw} - T_R)}{M_s \cdot (T_R - T_{fs} + T_{is})} \quad \text{[J/kg °C]}$$

$$\begin{bmatrix} B = C_{ps} \cdot M_w + H_k \\ T_R = \left(\frac{dT}{dt}\right) \cdot t_e \end{bmatrix} \quad (5)$$

where is

C_{ps} Specific heat capacity of sample (J/kg °C)
T_{fw} Water temperature at final state (°C)
T_{fs} Temperature of sample at final state (°C)
T_{is} Temperature of sample at initial state (°C)
M_s Mass of sample (kg)

The term $\left(\frac{dT}{dt}\right)$ was calculated from slope from the plot temperature vs. time for sample and equilibrium time from equilibrium state also for sample.

The density of dough was determined by weighing a known volume of the dough.

The thermal diffusivity was obtained from following equation:

$$\alpha = \frac{k}{\rho \cdot c_p} \quad \text{[m}^2\text{/s]} \quad (6)$$

where is

α Thermal diffusivity (m²/s)
k Thermal conductivity coefficient (W/m °C)
ρ Density (kg/m³)
c_p Specific heat capacity (J/kg °C)

The baking oven for batch baking of "Mlinci" dough is like tunnel without upper wall. Instead of upper wall there are crossbars at the 1.5 m from the hot surface. "Mlinci" dough was put on hot surface to bake, each side for 5.5 min. After baking they cross over to upper crossbars to dry for 15 min. Finally, "Mlinci" dough were cooled and packed.

The measurements of temperature inside the oven (hot surface and hot air) and on the "Mlinci" dough surface were conducted with surface thermocouple type K (-60°C to 300°C) with device TESTO 635 (Testo) with accuracy of ± 1°C. The surface temperature of "Mlinci" dough was measured at an interval of 26 min by putting smoothly the thermocouple on the surface of "Mlinci" dough, in such a way that it does not damage the "Mlinci" dough.

During baking of "Mlinci" dough in batch oven, heat is mainly transferred:

1. By conduction to the bottom of the "Mlinci" dough surface which is in contact with hot surface.
2. Partly by radiation to the surface of the "Mlinci" dough exposed to air.
3. By free convection to the exposed surface of the "Mlinci" dough.

The heat transfer between media (hot surface) and the product ("Mlinci" dough) takes place by conduction:

$$q_c = \frac{k \cdot A_M \cdot (T_h - T_i)}{x} \quad \text{[W]} \quad (7)$$

where is

k Thermal conductivity of "Mlinci" dough (W/m °C)
A_M Area of "Mlinci" dough in contact with hating medium (hot surface) (m²)
T_h Temperature of hot side of "Mlinci" dough in contact with hot surface (°C)
T_i Initial temperature of "Mlinci" dough (°C)
x Thickness of "Mlinci" dough (m)

The heat transferred by radiation during baking of "Mlinci" dough in batch oven can be neglected due to the construction of the oven. As mentioned above, the oven for batch baking the "Mlinci" dough is without upper cover.

The heat transfer between air and "Mlinci" dough takes place by free convection.

$$q_{fc} = h_{fc} \cdot A_M \cdot (T_a - T_M) \quad \text{[W]} \quad (8)$$

where is

h_{fc} Heat transfer coefficient for free convection (W/m² °C)
T_a Temperature of hot air (°C)
T_M Temperature of "Mlinci" dough surface exposed to air (°C)

Various parameters required for calculating individual heat transfer modes are presented in Table 2.

Results and discussion

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

The average value of thermal conductivity and specific heat capacity was 0.494 W/m °C and 2257 J/kg °C respectively as reported in Table 1 for thermal diffusivity of "Mlinci" dough of $2.034 \cdot 10^{-7}$ m²/s and density of 1076 kg/m³.

Theoretically, total heat transferred to “Mlinci” dough must be equal to the total heat absorbed by “Mlinci” dough. Heat transferred to “Mlinci” dough is equal to $q_t=q_c+q_{fc}$ and heat absorbed by “Mlinci” dough is equal to $q_a=q_s+q_l$. The sensible heat is given as:

$$q_s = \frac{W \cdot c_p (T_h - T_i)}{\Delta t} \quad [W] \qquad (9)$$

where is

W Weight of “Mlinci” dough (kg)
C_p Specific heat capacity of “Mlinci” dough (J/kg °C)
Δt Elapsed time (s)

The latent heat is given as:

$$q_l = \frac{H_{vap} \cdot \Delta M}{\Delta t} \quad [W] \qquad (10)$$

where is

H_{vap} Latent heat of vaporization of water (2256.97 kJ/kg)
ΔM Moisture mass loss of “Mlinci” dough during baking (kg)

The moisture loss was calculated from the initial moisture content of formed “Mlinci” dough and final moisture content of baked “Mlinci” dough (wet basis). Time taken for baking of “Mlinci” dough was also noted. All these data are presented in Table 2.

In the present study, the heat absorbed by “Mlinci” dough (293.86 W) and heat transferred to “Mlinci” dough (299.76 W) are in good agreement. The complete heat balance for baking of “Mlinci” dough in batch oven (transfer to a single “Mlinci” dough) is presented in Table 3.

The deviation of 1.9% is attributed to the heat of radiation, heat of fusion of fats, heat of reaction, heat of solution and heat of vaporization of volatile, which have been neglected (Gupta, 2001). The contribution of heat transferred by conduction was 96.09% and heat transferred by free convection was 3.91%. To calculate the transferred heat by convection, free convection heat transfer coefficient was obtained using the Nusselt number.

$$Nu = \rho(Gr, \Pr) \qquad (11)$$
$$Nu = a \cdot (Gr \cdot \Pr)^m$$

$$Nu = \frac{h_{fc} \cdot L}{k} \qquad (12)$$

From equation (12) the free convection heat transfer coefficient can be calculated using the following equation:

$$h_{fc} = Nu \cdot \frac{k}{L} \qquad (13)$$

Table 2. Various parameters required for obtaining individual heat transfer modes

1	The average specific heat of "Mlinci" dough	2.257 kJ/kg °C
2	The average thermal conductivity of "Mlinci" dough	0.494 W/m °C
3	Initial moisture content in "Mlinci" dough (wet basis)	30%
4	Final moisture content in "Mlinci" dough (wet basis)	14%
5	Weight of "Mlinci" dough	0.36907 kg
6	Temperature of heating medium (hot surface)	195.5 °C
7	Air temperature in the oven	70 °C
8	Temperature of "Mlinci" dough surface in contact with hot surface	52 °C
9	Initial temperature of "Mlinci" dough	35 °C
10	Linear dimension of "Mlinci" dough	0.1925 m
11	Area of "Mlinci" dough	0.0343 m^2
12	Thickness of "Mlinci" dough	0.001 m
13	Baking time	1560 s
14	Moisture removed from "Mlinci" dough	0.19684 kg
15	Heat transfer coefficient for free convection	9.756 W/m^2 °C
16	Thermal diffusivity of "Mlinci" dough	2.034·10^{-7} m^2/s
17	Density of "Mlinci" dough	1076 kg/m^3

Table 3. Complete heat balance for baking of “Mlinci” dough in batch oven (heat transfer to a single “Mlinci” dough)

	Contribution (W)	% of total heat
Total heat absorbed per "Mlinci" dough, q_a	239.86	100
As sensible heat, q_s	9.08	3.09
As latent heat, q_l	284.78	96.91
Total heat transferred per "Mlinci" dough, q_t	299.76	100
By conduction, q_c	288.05	96.09
By convection, q_{fc}	11.71	3.91

where is

Nu Nusselt number
Gr Grashof number
Pr Prandtl number
k Thermal conductivity for air at average temperature of film (W/m °C)
L Linear dimension of “Mlinci” dough (m)

The value of h_{fc} was calculated from Eq. (13) and substituted in Eq. (8) to obtain free convection, q_{fc}. The values are presented in Table 3. The parameters a and m from Eq. (11) were determined using literature. For $(Gr \cdot \Pr)$ equal to 10^3, the heat transferred is approximately equal to that

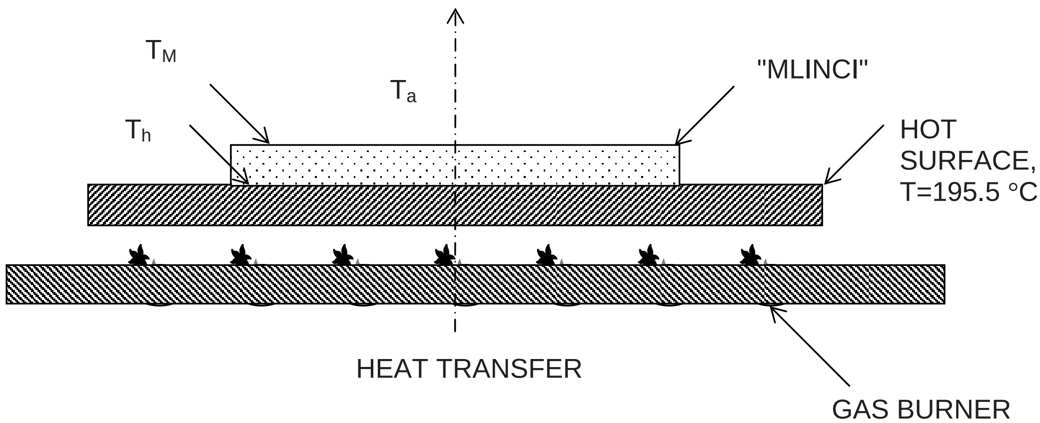

Figure 1. "Mlinci" dough in contact with hot surface in batch oven

due to conduction alone, but for $(Gr \cdot \mathrm{Pr})$ from 10^4 to 10^6, the heat transferred is given by $Nu=0.15\cdot(Gr \cdot \mathrm{Pr})^{0.25}$. For high values of $(Gr \cdot \mathrm{Pr})$, Nu is proportional to $(Gr \cdot \mathrm{Pr})^{1/3}$, showing that the heat is transferred not entirely by convection and is not influenced by distance between the surfaces (Coulson et al., 1980). For baking of "Mlinci" dough in batch oven the free convection heat transfer coefficient was obtained using the following equation:

$$h = 0.14 \cdot (Gr \cdot \mathrm{Pr})^{1/3} \cdot \frac{k}{L} \qquad (14)$$

Figure 1 is shows course of heat transfer during baking of "Mlinci" dough and position of "Mlinci" dough placed on hot surface that is situated above heat source. For horizontal plates facing heated surface up where the $(Gr \cdot \mathrm{Pr})$ is from $2\cdot10^7$ to $3\cdot10^{10}$ the parameters are a=0.14 and m=1/3 (Pitts and Sissom, 1977).

Total heat absorbed by "Mlinci" dough, which comprised of sensible and latent heat was calculated. The contribution of latent heat (284.78 W) was about 93% more than the sensible heat (9.08 W) because large amount of heat is required for baking of "Mlinci" dough as inside moisture has to be converted from liquid phase to vapour phase. The "Mlinci" dough is declared as a long lasting product due to amount of final moisture content (14%).

Conclusions

During baking of "Mlinci" dough in batch oven combination of different heat transfer modes occurs. Heat was transferred by conduction and convection. The heat transfer by radiation was neglected due to oven design. The major contribution is due to conduction, 96.09%. Thus, it is required to control the amount of heat supplied to the product by the individual modes, particularly by conduction. The obtained heat transfer modes and thermal parameters can be used for designing the continuous oven for baking "Mlinci" dough.

Appendix A

Calculation of individual heat transfer modes

(i) By conduction

$$q_c = \frac{k \cdot A_M \cdot (T_h - T_i)}{x}$$

$$q_c = \frac{0.494 \cdot 0.0343 \cdot (52 - 35)}{0.001}$$

(ii) By free convection

$$q_{fc} = h_{fc} \cdot A_M \cdot (T_a - T_M)$$

$$h_{fc} = 0.14 \cdot (Gr \cdot \mathrm{Pr})^{1/3} \cdot \frac{k}{L}$$

$$h_{fc} = 0.14 \cdot (1.42 \cdot 10^8)^{0.33} \cdot \frac{0.027375}{0.1925}$$

$$h_{fc} = 9.745 \ \mathrm{W/m^2 {}^\circ}C$$

$$q_{fc} = 9.756 \cdot 0.0343 \cdot (70 - 35)$$

$$q_{fc} = 11.71 \ \mathrm{W}$$

The total heat transferred to single "Mlinci" dough is equal to heat transferred by conduction and by free convection (neglecting heat transferred by radiation)

$$q_t = q_c + q_{fc}$$

$$q_t = 288.05 + 11.71$$

$$q_t = 299.76 \ \mathrm{W}$$

The total heat absorbed by the product is calculated, from the rise in temperature of the product and latent heat of vaporization of moisture (neglecting heat of reaction etc.), i.e.,

$$q_a = q_s + q_l$$

$$q_a = \frac{W \cdot c_p \cdot (T_h - T_i)}{\Delta t} + \frac{H_{vap} \cdot \Delta M}{\Delta t}$$

$$q_a = \frac{0.36907 \cdot 2257 \cdot (52 - 35)}{1560} + \frac{2256.97 \cdot 10^3 \cdot 0.19684}{1560}$$

$$q_a = 293.86 \text{ W}$$

It takes 26 min for baking the “Mlinci” dough in batch oven or 1560 s and the moisture removal is 196.84 g during this period.

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