The Effect of Baking Time and Baking Temperature on Porosity, Density and Thermal conductivity of the Part-Baked Sangak Bread, during Baking

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Abstract— **Sangak bread, for its nutritional value, aroma, and special taste has a high potential to be industrially mass produced and supplied to the market, part-baked. In this paper, the effect baking temperature (in four levels of: 230, 250, 270 and 290 degrees Celsius) on the moisture content, porosity, apparent density and thermal conductivity during special times of baking (in30, 60, 90, 120, 150, 180 seconds) in the part-baked Sangak bread were studied. The performed tests indicated a significant reduction of moisture and apparent density as the result of increasing the baking temperature. The results of tests show a significant increase in porosity with the increase in baking time and baking temperature. The effective thermal conductivity was measured using the thermal conductivity probe. Based on the results of the test, the increase in baking temperature, due to their effects on increase in porosity and reduction of moisture content, causes reduction in the thermal conductivity. In this paper, four models (Series, Parallel, Krischer , and Maxwell) were developed for describing the thermal conductivity. The effective thermal conductivity data predicted with Krischer model were really compatible with the experimental data. In addition, the distribution factor (f_λ) was evaluated by using Krischer model. Results showed an increase in this parameter with the increase in baking time and baking temperature.**

Keywords; Thermal conductivity, Thermal conductivity model, Line heat source, Porosity, Image processing, apparent density

Nomenclature	
a_w	water activity
D	Diffusivity of water vapor in air,$m^2 s^{-1}$
$f_{eva\text{-}con}$	Resistance factor against vapor transport
f_λ	Structural factor or distribution factor of Krischer model
I	Current through heater wire, A
L_0	Latent heat of evaporation, J mol^{-1}
m	Slope of the linear portion of the plot of the temperature vs. ln(time)
N	Number of evidence
P	Total pressure, Pa
P_{sat}	Saturated pressure of water vapor, Pa
Q	Power generated by probe heater, Wm^{-1}
R	Perfect gas constant, 8.314510 J $mol^{-1} K^{-1}$
T	Temperature, K
x	Mass fraction, kg/kg product
Greek letters	
λ	Thermal conductivity, W $m^{-1} K^{-1}$
ε	Volume fraction, porosity m^3/m^3
ρ	Density, kg m^{-3}
υ	Volume fraction
Subscripts	
a	Correspond of pores (voids)
air	air
apparent	apparent
c	continue
d	dispersed
eva-con	Evaporation-condensation
exp	experimental
i	Component i
pre	predective
sat	saturated
T	total

I. INTRODUCTION

Sangak bread is referred to a kind of flat bread which is made of whole wheat flour, water, salt, sour dough or industrial yeast and baked in a certain way on some hot gravel. Among the traditional Iranian breads, Sangak bread is the only kind of bread that uses indirect fire for baking. This bread, for its nutritional value, aroma, and special taste has a high potential to be industrially mass produced and supplied to the market as part-baked. In producing the part-baked Sangak bread, the dough is processed to the last stage; i.e., baking. However, the baking happens in its lowest level in which a minimum color change happens. As a result, studying the baking process to produce a high quality product and also the conservation of energy seem to be essential. The heat transfer is one of the main phenomena during baking. The heat transfer analysis in different materials requires studying the thermo physical characteristic changes and thermal conductivity being as one of the most important ones. Food stuffs' thermal conductivity can be measured or be mathematically calculated. Methods used for measuring thermal conductivity can be divided into two groups: steady-state methods and unsteady-state methods (or transient methods) [1]. Among transient methods, the line heat source probe method is more practical than other methods. Among the advantages of this method, we can mention the short measurement time and the little increase in temperature (only a few centigrade) [2].

Due to the physicochemical characteristic and temperature effects on the thermal conductivity of the materials, the prediction of this parameter in food stuff with respect to other features (like density, porosity, special heat capacity, and enthalpy) is more complicated. To estimate the thermal conductivity, some models were developed based on some experiments [3] and some equations based on some theoretical perspectives [4]. Among these models, the parallel, perpendicular, Krischer, and dispersed phase are of more importance and reputation [7-4].

In porous foods like bread, developing a model to estimate thermal conductivity level due to the evaporation-condensation process in the pores is very difficult. The appearance of a temperature gradient in porous materials causes moisture migrations vapor in pore space. Water evaporates at the high temperature side, diffusion according to the vapor pressure gradient caused by temperature gradient, and condensate at the low temperature side [8]. Thus the latent heat is transported throughout the pores. Hamdami et al. found that this phenomenon, even in sub-zero temperatures, causes an increase in heat transfer through the increase in effective thermal conductivity [9]. They have estimated the amount of heat transfer due to this phenomenon, using the equation which was previously provided by Sakiyama.

$\lambda_{eva\text{-}con}$ which is equal to heat transfer resulted from the evaporation-condensation (equation 1). By considering the effect of the latent heat transport, the effective thermal conductivity in the pores was given by equation 2. Where $f_{eva\text{-}con}$ is the resistance factor against vapor diffusion.

$$\lambda_{eva-con}(T) = \frac{\mathrm{D}}{\mathrm{RT}} \frac{P}{P - a_w P_{sat}} L_0 a_w \frac{dP_{sat}}{dT} 1 \quad (1)$$

$$\lambda_{\mathrm{a}}(\Theta) = \lambda_{\mathrm{air}}(\Theta) + \lambda_{\mathrm{eva-con}}(\Theta) f_{\mathrm{eva-con}} \quad (2)$$

In the Following we will point out some of the researches done on effective thermal conductivity in bakery products. Sablani et al., in 2002, used a method called "artificial neural network" (ANN) made a model for changes in thermal conductivity in bakery products as a function of moisture content, temperature, and apparent density [10]. Hamdami et al., based on the Krischer and Maxwell models, and considering the evaporation-condensation phenomenon developed a model for estimating the effective thermal conductivity in bread (food stuff with high porosity) during the freezing process [11]. Carson et al. (2004) studied the effect of porosity on the effective thermal conductivity [12]. In addition, they presented a model for estimating the effective thermal conductivity in non-frozen porous food items in 2006 [13]. Jury et al. presented a model for estimating the effective thermal conductivity during baking part-baked bread [14]. Monteau used the inverse method to develop a model for estimating the effective thermal conductivity of sandwich bread and by using an analytical method, he studied the effect of temperature and water content on thermal conductivity in 2008 [15]. Zuniga and Le-bail found a relation between the changes in thermal conductivity under the effect of porosity during fermentation time [16]. Among the related researches on thermal conductivity of the bakery products, no one has ever studied the effect of baking time and baking temperature on the effective thermal conductivity of flat bread during the baking process. Therefore, doing research on this topic seems to be necessary. So, this research is following two goals: a) studying the effect of the baking time and baking temperature and other effective parameters (like, moisture level, porosity, density during baking) on this parameter, and b) developing a mathematical model for predicting the thermal conductivity of the bread during baking.

II. Materials and Methods

A. Samples Preparations

Sangak bread dough ingredients are : 100% dough, 1% salt, 1% activated dry yeast (Kelarmaayeh factory,ShahreKord, Iran) and 100% water. To make the part-baked Sangak bread, we obtained whole wheat flour from a traditional bakery in Esfhahan (the composition of the used flour in producing part-baked Sangak bread is shown in table 1).

Table 1: The chemical analysis of the used dough in tests (percent)

	ash	protein	carbohydrate*	fat	moisture
Flour	1.32±0.068	11.035±0.12	72.095±0.11	1.55±0.226	14±0.045
Dough	1.114±0.068	5.131±0.12	33.172±0.11	0.721±0.226	59.86±0.045

carbohydrate*=100-(ash +protein +fat +moisture)

At first, all the dry ingredients were mixed together at 25 degrees Celsius, using a fixed mixer (HOBART mixer, model C-100, USA) and after turning it into a homogeneous mixture, we added water and the other liquid materials. The yeast suspension was added at the end of the mixing stage. The mixing process took 15 minutes with a speed of 50 RPM and after the end of mixing, the dough was left at rest inside the mixer for 10 minutes.

To ferment, the prepared dough was put it into the fermentation chamber with saturated relative humidity and 30 C° temperature for 30 minutes. To achieve uniformity in sample’s thickness, we used a rolling pin to spread dough in specific mold (Figure 1) and finally after taking out dough from the mold, square shaped dough with 15 cm dimensions and 5 mm thickness was obtained.

The prepared dough is put in oven (BOCSH, HBA73B550, Germany) at different temperatures (230, 250, 270, 290 C°) on hot aluminum slab with 1 cm thickness in temperature equilibrium with the oven's temperature and they were taken out from the oven at certain time intervals (30, 60, 90, 120, 150, 180 seconds).

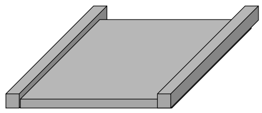

Figure 1: The mold's image

Moisture content of Sangak’s dough were evaluated during baking according to the AACC method 44-15A with an air oven (Memmert, UNB400, Germany) [17].

B. Porosity and Apparent Density Measurements

To measure the porosity, the sample part-baked Sangak bread was put into into a freezing tunnel of -24 °C whit a polyethylene cover (humidity insolent) for 10 minutes and then one piece of it was cut out using a surgery blade. The cut slice was quickly (before thawing) put onto a scanner screen and photographed with 1200 dpi resolution. It should also be mentioned that in photography stage we should always use a scale (a ruler), so that we can analyze the pores in the bread better. To analyze the photos of the sliced bread, we first edited them by Photoshop Studio CS4 software to clarify borders between the pores. Then, by showing the bright spots as white and dark spots as black, we turned the color of the photo into black & white. Since the holes were farther from the scanner, they received less light and looked darker, but the holes' walls received more light and looked white in the final photo (Figure 2).

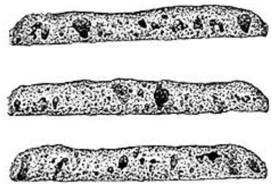

Figure 2: A sample edited Figure by Photoshop software

Finally, the porosity of the samples was determined using the black and white photo with the help of *Image J* software. These experiments were repeated 3 times and each time on 3 different slices in different position and eventually, the results were averaged and reported.

The apparent density of the sample bread was measured in two different methods. In the first method, the apparent density of the bread was measured using the rapeseed displacement method (AACC 10-5) and in the second method, after estimating the real density of the samples, with the help of series model (equation 3), the apparent density of the bread was obtained using equation 4 with applying the porosity.

$$\frac{1}{\rho_T} = \sum_{i=1}^{N} \frac{x_i}{\rho_i} \quad (3)$$

$$\rho_{app} = (1-\varepsilon)\rho_T \quad (4)$$

C. Thermal conductivity

Thermal conductivity of the samples was measured using the line heat source method. The used probe was similar to the one designed and built by Sweat and Parmelee [18]. To measure the thermal conductivity, a developed system like the one by McGinnis, was used (Figure 3) [19]. This system consists of power supply, multi-meter, thermal conductivity probe, data logger, and certain resistance. A DC power supply with the capacity of generating a constant difference potential of 0 to 30 volts and accuracy of 0.001 was used.

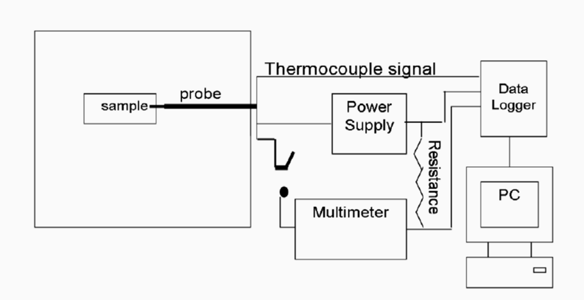

Figure 3. The circuit used for measuring the thermal conductivity

The applied voltage was carefully controlled by multi-meter with±0.1accuracy, and during the experiment the voltage, electric current intensity, and the temperature were recorded by the data logger. In this method, to measure the thermal conductivity, the bread samples with dimensions of 1.5*1.5 cm were cut out, and then were put on top of each other in a way that created a rectangular cube with dimensions of 1.5*1.5*6 cm. Then, the obtained rectangular cube was put in a polyethylene cover (moisture insolent) and the thermal conductivity probe was placed in the center of the rectangular cube (area of 1.5*1.5) and in line with its axis. After reaching the sample's temperature to 30 °C inside the incubator, an electric current with a specific intensity was applied to the probe. According to Hamdami et al.'s suggestion for increasing the accuracy of the experiment, the electric current intensity was adjusted in such a way that the probe showed a 10-degrees increase in its temperature in just 8 seconds [20]. The thermal conductivity of the material (λ), was determined from the slope of the temperature-natural logarithm of time (m) diagram, and with the help of equation 5. Q represents the generated heat by the thermal element and is calculable by equation 6.

$$\lambda = \frac{Q}{4\pi m} \quad (5)$$

$$Q = RI^2 \quad (6)$$

From the theoretical aspect, the diagram of time natural logarithm versus the temperature had to be a straight line, but because of the thickness of the probe, a time delay was observed in the beginning stages (Figure 4 shows an example of this diagram) [21] .

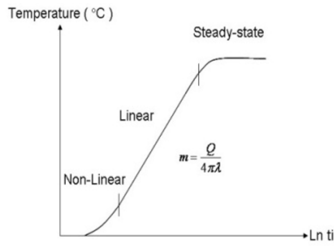

Figure 4. The diagram of the temperature changes versus ln(time)

To calibrate the probe, the thermal conductivity of glycerin and water (Agar gel 0.5%) in temperature range of 5 to 25 °C was measured. Considering the known value of thermal conductivity of glycerin and water, the probe's thermal element resistance (R = 161.2 Ωm^{-1}) was calculated[11]. This experiment was repeated 5 times and the maximum and the minimum measured values were eliminated as outlier values.

D. Thermal conductivity Modeling

To develop the math model for predicting the effective thermal conductivity of Sangak bread during baking, 4 models were used: series, parallel, Krischer, and Maxwell. We will briefly explain these models.

1. The Parallel Model:

In this model, the different ingredients of a foodstuff are considered as parallel resistors and in the direction of heat transfer and the effective thermal conductivity is calculable from the equations 7 & 8.

$$\varepsilon_i = \frac{x_i/\rho_i}{\sum\left(\frac{x_i}{\rho_i}\right)} \quad (7)$$

$$\lambda_{pa} = \sum_{i=1}^{N} \lambda_i \varepsilon_i \quad (8)$$

2. The Series Model

In the series model, the layers of the food item are perpendicular to the direction of the heat transfer. Thermal conductivity in this model is calculated as the harmonic average by using the equation 9.

$$\frac{1}{\lambda_{se}} = \sum_{i=1}^{N} \frac{\varepsilon_i}{\lambda_i} \quad (9)$$

3. The Random Distribution of Maxwell Model

By implementing a few different layouts (from the perspective of continuous or dispersed) in Maxwell model and selecting their best, we can to some extent understand the layout of the food ingredients. In this study, the Maxwell's thermal conductivity model was developed in 5 step for estimating the thermal conductivity of Sangak bread (Schematic image 5):

This model can closely estimate the thermal conductivity value to its actual value, because it doesn't have the limitations of the previous methods for geometrical conditions of the food products' components.

$$\lambda_{max} = \lambda_c \frac{2\lambda_c + \lambda_d - 2\varepsilon_d(\lambda_c - \lambda_d)}{2\lambda_c + \lambda_d + \varepsilon_d(\lambda_c - \lambda_d)} \quad (10)$$

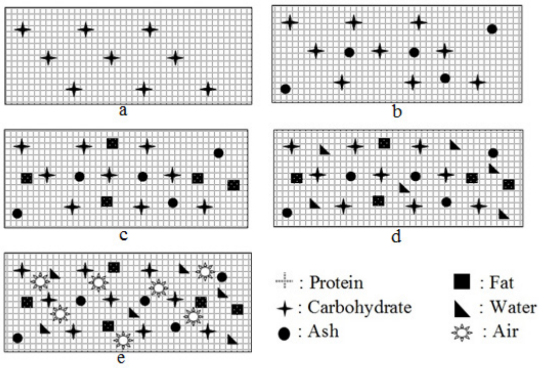

Figure 5: step of Maxwell model developing
a. Continuous phase as protein and dispersed phase of carbohydrate
b. Continuous phase as protein and carbohydrate and dispersed phase of ash
c. Continuous phase as protein, carbohydrate and ash and dispersed phase of fat
d. Continuous phase as protein, carbohydrate, ash and fat and dispersed phase of water
e. Continuous phase as protein, carbohydrate, ash, fat and water and dispersed phase of air

4. Krischer Model

Krischer presented a relatively good and practical model for predicting the effective thermal conductivity in porous food stuff (equation 11).

$$\lambda_{kr} = \frac{1}{\frac{1-f_\lambda}{\lambda_{pa}} + \frac{f_\lambda}{\lambda_{se}}} \quad (11)$$

The numerical value of the distribution factor (f) as an indicator for structure characteristic of the substance (ratio of series to parallel structure) changes in a range of 0 to 1 [9]. To determine this parameter, a comparison between the predicted values of thermal conductivity by the model with the measured data which was obtained with the help of a curve fitting tool and the Mathlab software in such a way that the best fitting achieved was used. By studying the trend of distribution factor changes during baking, the effect of baking temperature and the baking time on the structure of the bread is better understood.

III. Statistical Analysis

These tests were performed in a completely random settings and in time intervals of (30, 60, 90, 120, 150, 180 seconds) and with 4 different baking temperatures (230, 250, 270, 290 degrees Celsius) and three times repetition. The Anova model and SAS 8.0 software were used for the statistical analysis. In addition, by comparing the averages of each feature, using LSD test, and the effect of the reciprocal factors of baking time and baking temperature, using LS Means test were measured.

IV. Results and Discussions:

Tables 3, 4, and 5 show the effect of baking time and baking temperature using the LSD test, on the measured factors in this test.

A. Moisture

Figure 6 shows the changes in moisture content of the dough during baking in various temperatures. According to Figure 6, with an increase in the temperature and baking time the amount of moisture decreases (Figure 6 and tables 3 and 4). The increase in baking temperature with the simultaneous increase in partial pressure gradient of the water that exists between the surface of the bread and the hot air inside the oven and the moisture diffusion index in the bread causes an increase in dehydration in the bread during baking.

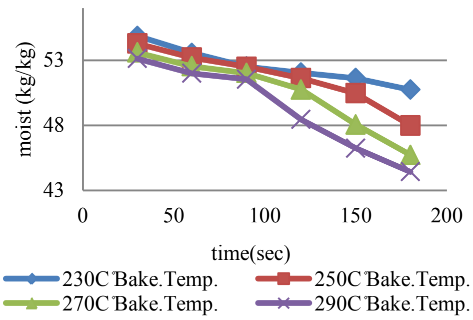

Figure 6 :moisture percentage changes of 60 min fermented dough in various baking temperature Porosity and Density

Figure 7 shows the changes in porosity in part-baked bread in different baking temperatures as a function of baking time. As it is observed, following an increase in baking temperature, the porosity of bread increases (Figure 7 and tables 3 and 4). This increase is mainly due to the effect of temperature increase in intensifying the vapor pressure of moisture evaporation. This is because the increase in baking temperature will cause a falling trend in moisture during baking. The increase in pressure due to the increase in temperature in the beginning of the baking period causes a growth in most pores and during the end of the baking period it raptures the pores. In addition, with an increase in the baking temperature, more water is evaporated and the space of the evaporated water is refilled with air or water vapor [23 ,22].

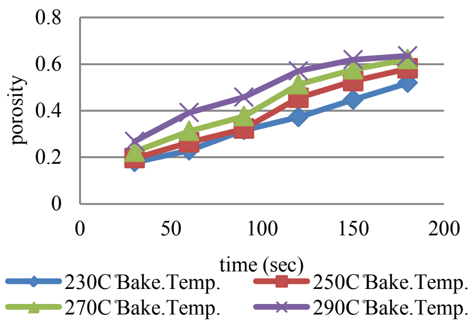

Figure 7 : the porosity percentage changes of 60 min fermented dough in various baking temperature

The resulted equation from linear regression for describing the relation between the measured apparent density and the estimated values by series method will be discussed below (equation 13):

RMSE equal to 0.592 and the slope close to 1 were show a high cohesion between the obtained data by the two discussed methods. This determines the suitability of the series model in estimating the apparent density and correctness of the applied adjustments in estimating the porosity using the image processing method.

Figure 8 shows the changes in Sangak bread's apparent density changes resulted from dough as a function of baking time in various baking temperatures. As it was observed, by increasing the temperature and baking time, the apparent density of Sangak bread samples decreases (Figure 8 and table 3 and 4). The declining trend of the apparent density with the increase in baking temperature and time can be related to the reduction in moisture and increase in porosity in Sangak's samples [24].

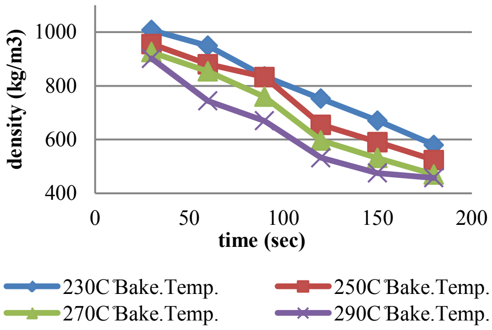

Figure 8 : apparent density changes of 60 min fermented dough in various baking temperature

B. *Thermal conductivity and Distribution factor*

Figure 9 shows the thermal conductivity changes in the bread during the baking of dough in various baking temperatures. The test results show that with an increase in baking temperature and time, the effective thermal conductivity of bread decreases and the ratio of the series structures increases with respect to the parallel structures (tables 3 and 4, and Figures 9 and 10).

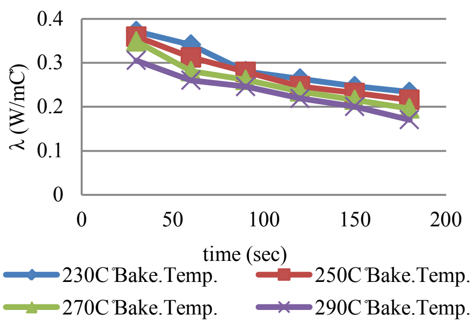

Figure 9 :the thermal conductivity changes of 60 min fermented dough in various baking temperature

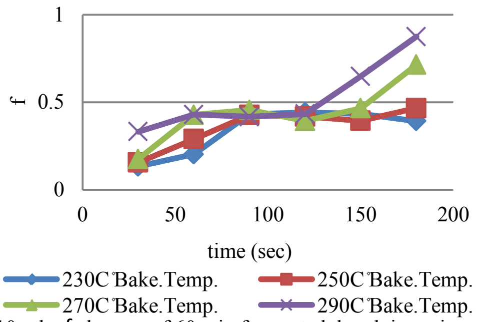

Figure 10 : the f changes of 60 min fermented dough in various baking temperature

$$y = 0.9692X + 7.5004, \quad r=0.999 \tag{13}$$

The reduction in effective thermal conductivity and increase in the ratio of series to parallel structures can be related to the increase in porosity and decrease in moisture content of the bread in reaction to the increase in temperature and baking time [26 ,25].

C. *Selecting the Best Model*

To select a suitable model for describing the effective thermal conductivity of Sangak bread, the correlation coefficient (r) and the root mean square errors (RMSE) between the experimental data and the predicted data by each model were compared, and finally a model with maximum coefficient of correlation and minimum RMSE was selected as a suitable model for describing the Sangak bread thermal conductivity during baking .

Table 2 shows the calculated values for r and RMSE for the experimental data and the predicted data by the parallel, series, Krischer and Maxwell models.

Table 2: values for r and RMSE for the experimental data and the predicted data by the parallel, series, Krischer and Maxwell models

	series	parallel	krischer	maxwell
RMSE	0.134	0.278	0.160	0.021
r	0.94	0.96	0.99	0.97

Figure 11 also shows a comparison between the measured thermal conductivity and the predicted data with the help of series, parallel, Maxwell, and Krischer models during the baking dough in 270 °C. As it was observed, the maximum conformity with the highest coefficient of correlation (r) and the minimum RMSE belongs to the Krischer model (table 2 and Figure 11). Therefore, Krischer model can be used to describe and predict the effective thermal conductivity changes in Sangak bread.

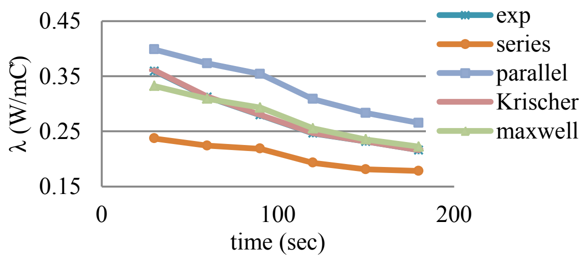

Figure 11: a comparison between the measured thermal conductivity and the predicted data with the help of series, parallel, Maxwell, and Krischer models during baking

V. CONCLUSION

In this paper, the effect of fermentation time and baking time on the moisture content, apparent density, porosity, and effective thermal conductivity of part-baked Sangak bread during various baking times were examined and analyzed. The results showed that the reduction in moisture content with the increase in baking temperature is under the influence of the increase in temperature gradient and its

effect on evaporation increase from the evaporation's surface. In addition, increase in baking temperature by the rise in produced vapor's pressure inside the pores, will cause a rise in porosity and reduction in part-baked Sangak bread's thermal conductivity. With the reduction in moisture content and increase in porosity under the influence of baking temperature and fermentation time increase, the apparent density also decreases. In this study, four models (parallel, series, Krischer and Maxwell) were developed to estimate the effective thermal conductivity of Sangak bread. Among these models, the predicted data by the Krischer model was well conformed to the measured thermal conductivity values. The estimated distribution factor (f_λ) using the Krischer model which is an indicator of the ratio of the series structures to the parallel structures was increased by the baking time and baking temperature.

Table 3: The Table for Comparing the Mean for the Measured Parameters in Various Baking Times

Baking temperature (C)	parameter				
	Apparent density (kg/m^3)	f_λ	Λ(W/mC)	Moisture content (kg/kg)	porosity
230	821.1 ^{a}	0.32^d	0.299 ^{a}	52.9^a	0.32 ^{d}
250	753.8 ^{b}	0.35^c	0.281 ^{b}	51.8^b	0.38 ^{c}
270	714.7 ^{c}	0.40^b	0.265 ^{c}	50.9 ^{c}	0.41 ^{b}
290	641.5 ^{d}	0.48^a	0.239 ^{d}	49.8 ^{d}	0.48 ^{a}

For each parameter, the mean is shown with at least one similar letter indicating no significant changes in the probability levels with P = 0.05 and using the LSD statistical test.

Table 4: The Table for Comparing the Mean for the Measured Parameters in Various Baking Temperatures

Baking time (sec)	Parameter				
	Apparent density (kg/m^3)	f_λ	Λ(W/mC)	Moisture content (kg/kg)	porosity
30	957.9 ^{a}	0.17^f	0.361 ^{a}	54.6 ^{a}	0.21 ^{f}
60	869.1 ^{b}	0.31 ^{e}	0.308 ^{b}	53.1 ^{b}	0.29 ^{e}
90	780.4^c	0.39^d	0.273^c	52.2 ^{c}	0.37^d
120	674.9^d	0.41^c	0.249 ^{d}	51.2 ^{d}	0.45 ^{c}
150	591.1^e	0.46^b	0.229^e	49.6 ^{e}	0.52^b
180	523.3 ^{f}	0.57^a	0.207^f	47.7^f	0.58 ^{a}

For each parameter, the mean is shown with at least one similar letter indicating no significant changes in the probability levels with P = 0.05 and using the LSD statistical test.

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