Iranian Food Science and Technology Research Journal
Vol. 11, No. 3, Agu. Sep. 2015, p. 225-235

نشریه پژوهشهای علوم و صنایع غذایی ایران
جلد ۱۱، شماره ۳، مرداد - شهریور ۱۳۹۴، ص. ۲۳۵-۲۲۵

Baking-drying kinetics of crisp bread:
The influence of bran content and baking temperature

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Received: 2013.09.30
Accepted: 2014.05.31

Abstract

In this study, mathematical modeling of hot air baking-drying of thin-layer crisp bread was investigated. Thin-layer drying process were conducted under three different temperatures of 110, 150 and 190 °C at a constant air velocity of 0.5±0.1 m/s and absolute humidity of 0.6 ± 0.04g water/kg dry air. It was found that the baking-drying process occurred in falling rate period over the baking-drying times. Eight well-known thin-layer baking-drying models were fitted to the baking-drying experimental data of crisp bread, implementing non-linear regression analysis techniques. Based on the coefficient of determination (R^2) and root mean square error (RMSE) values, it was concluded that the best models in terms of fitting performance for hot air baking-drying of bran free crisp bread were Wang & Singh and Logarithmic while for whole-wheat crisp bread were Page, Logarithmic and Wang & Singh. The moisture transfer from crisp bread was described using the Fick's diffusion model. The effective diffusivity was within the range of 2.88×10^{-8} to 1.11×10^{-7} m^2/s for bran free crisp bread and from 2.47×10^{-8} to 8.84×10^{-8} m^2/s for whole-wheat crisp bread over the temperature range. The activation energy for bran free and whole-wheat crisp bread was found to be 25.22 and 23.43 kJ/mol, respectively..

Keywords: Bran, Bread, Drying Modeling, Diffusivity, Activation Energy.

Introduction

Crisp bread is simple flat and dry type of bread made with flour, water, and salt and then thoroughly rolled into flattened dough. Crisp breads are light and have very long shelf life (Edward, 2007). However, in recent years there has been renewed interest in crisp bread in the world. Many crispy flat types of bread are made with yeast and sourdough, such as Iranian crispy flat bread, although some flat bread is unleavened and made without yeast or sourdough culture. Crispy flat breads can range from one millimeter to a few centimeters thick. It is a common belief that whole-wheat crisp breads are more appropriate for a diabetic diet, as they have less hyperglycemic effect (Mesci *et al*, 2008).

During bread baking, heat and moisture transport take place in the dough simultaneously and interdependently, and involve three major changes (Mondale & Datta, 2008): (a) Water vaporizes at the cell/dough interface and gases accumulated during fermentation (CO_2, ethanol) or generated by chemical raising agents are also vaporized: the cell volume increases provided that the dough film retains gases and is deformable;(b) Starch gelatinization and protein coagulation transform the viscous dough into a mainly elastic crumb; these rheological changes limit the cell growth described in section (a) and enhance pressure build-up;(c) The structure with gas cells separated by films is transformed into a porous structure with inter-connected pores. The crust and crumb come from the same original dough, but their final properties differ according to a distinct local heat-moisture treatment. Crispy texture is also associated with low moisture content and water activity, when starch and gluten matrix are in a glassy state making cells walls more prone to fracture (Stokes & Donald, 2000). Baking is generally modeled as simultaneous heat and moisture transfer: convective, radiative and conductive type of heat transfer or their different combinations from the oven cavity toward the product surface followed by an internal heat

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diffusion, and an internal moisture diffusion (either liquid or vapor), internal and surface evaporation and a convective surface moisture removal mechanisms. The baking-drying kinetics of crisp bread is a complex phenomenon and requires dependable models to predict its baking-drying behavior.There is three types of thin-layer drying models: theoretical, semi-theoretical and empirical (Midilli *et al.,* 2002; Demirats *et al.,* 1998). The theoretical model depends on the physical characteristics of grains. The empirical model presents a direct relationship between average moisture and baking-drying time by means of regression analysis (Ozdemir and Devres, 1999). Semi-theoretical is between the theoretical and empirical models, which is derived from Fick's second law of diffusion. It is used in the form of the Page model, the Modified Page model, the Henderson model and other models (Midilli *et al.,* 2002).

Modeling of drying process using mathematical models has been studied in the drying of fruits, vegetables, seafood and many other agriculture or crop products (Aghbashlo *et al*., 2009). Zanoni *et al.* (1994) investigated mathematical model of baking and validated experimentally. They described heat and mass transport phenomena during baking of a cylindrical bread sample using finite difference numerical method. Zanoni *et al*, (1995) determined the thermal diffusivity by comparing the temperature profile obtained experimentally during heating of bread at 100 °C in an oven and the apparent density of bread crust and crumb as a function of porosity. Baik and Marcotte (2002) studied the moisture diffusivity during baking of very thin slabs of cake batter neglecting the temperature gradient effect and assuming negligible external mass transfer resistance. Demirkol, *et al.,* (2006) published their research on the moisture diffusivity determination of a baking biscuit at different oven temperatures. Soleimai *et al.* (2013) studied the baking kinetics of bread to find out the moisture loss behavior of that during baking process. They reported that among the drying models, the Page model gave the best results and showed the closest data compared to the experimental data. Guillard *et al*, (2004) validated a model for predicting moisture transfer in agar gel/biscuit composite food. all the models developed deal with intermediate or high aw products and cylindrical, non commercial food geometries. It would be interesting to validate such models on more realistic geometries with low aw products. Diffusivity models determined by these authors were then tested in drying kinetics and moisture migration experiments in agar gel/biscuit composite food respectively. Adjustment of parameters was required for a best fit of experimental data.

The objective of the present study was to find out the baking-drying behavior of crisp bread in different temperature and bran effect to predict its moisture content during baking-drying process. For this reason, eight well-known mathematical models were used to describe the baking-drying process of crisp bread as a function of bran and temperature. In addition, two drying parameters consisting effective moisture diffusivity and activation energy were calculated.

Materials and methods

Basic ingredients

Commercial wheat flours of 13.6% moisture (ICC 110/1), 14.25% proteins (ICC 105/2), 0.45% ash (ICC104/1), 0.85% fat (ICC 136), 37% wet gluten (ICC 155) and 405 s Falling number (ICC 107/1) was purchased from local market. Compressed yeast (purchased in the local bakery) was used as a starter.

Bread making process

Samples of bread dough were prepared using the straight dough method with the following formulations: (1) bran free wheat flour (85% extraction) (10 kg), compressed yeast (1%, flour basis), salt (1.5%, flour basis) and water necessary to give optimum consistency of 500 Brabender Units (BU) in a Farinograph, following the ICC Method (ICC 115/1), was used in this study. In formulation (2), bran free wheat flour was replaced with wheat bran at 15% levels. Total dietary fiber

(TDF) content of white flour and bran was determined, in triplicate, according to the AOAC method (AOAC, 1995).

All the ingredients were mixed for 10 min in a home multi-function food processor. The prepared dough were put in stainless steel trays and for surviving proving stage stored in an experimental fermentation oven for 60 min at 35°C and 85% relative humidity. After first resting, dough samples were formed by dividing and weighing the dough into 70 g cylinder dough balls and rounded with hand until uniform dough samples (0.20 m length and 0.015 m diameters) were achieved and then let to rest for 10 min. Dough samples were baked in an electric static oven (Delongi EO1258, Italy) in forced convection (with 0.5 m/s air velocity). Three baking temperatures were selected for bread baking: 110, 150, 190°C. The tray with samples was placed in the central zone of the oven. All baking tests were conducted in triplicate. Moisture loss was determined by weighing the tray containing the sample, interrupting the baking process every 5 min using a digital balance with 0.01 g accuracy. This procedure took 5-10 s approximately, thus it was assumed that no significant perturbation was introduced in moisture measurements.

Mathematical modeling

Eight well-known models of thin-layer baking-drying were investigated to find the most suitable model for the baking-drying process of crisp bread (Table 1). The moisture ratio (MR) was defined by:

$$\mathrm{MR} = \frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} \tag{1}$$

Where, M and M_0 are the moisture content of the samples at any baking-drying time and initial moisture content, respectively. The moisture ratio equation was simplified to M/M_0 as the value of M_e (equilibrium moisture content) is relatively small compare to M or M_0 (Akgun and Doymaz, 2005; Doymaz, 2004). In a general manner, the performance of a model is evaluated based on the comparison between the computed output (predicted) and input (experimental) data. In this study, the obtained predicted data for each model was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE) (Eqs. 2 and 3, respectively). A model with the maximum of R^2 and the minimum of RMSE shows the best performance (Kingsly and Singh, 2007):

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - \overline{MR}_{\exp})^2 (MR_{pre,i} - \overline{MR}_{pre})^2}{\sum_{i=1}^{N}(MR_{\exp,i} - \overline{MR}_{\exp})^2 \sum_{i=1}^{N}(MR_{pre,i} - \overline{MR}_{pre})^2} \tag{2}$$

Table 1. Mathematical models for thin-layer baking-drying

Model name	Model equation	References
Newton	$MR = \exp(-kt)$	Westerman and White, 1973
Page	$MR = \exp(-kt^n)$	Guarte, 1996
Modified Page	$MR = \exp(-kt)^n$	Yaldiz *et al.*, 2001
Henderson and Pabis	$MR = a\exp(-kt)$	Yagcioglu *et al.*, 1999
Logarithmic	$MR = a\exp(-kt) + c$	Yaldiz *et al*, 2001
Two-term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Rahman, 1998
Wang and Sing	$MR = 1 + at + bt^2$	Ozdemir and Devres, 1999
Midilli et al.	$MR = a\exp(-kt^n) + bt$	Sacilik *et al.*, 2006

Table 2. Chemical composition of wheat flour, wheat bran and bran free wheat flour

Composition	Whole wheat flour	bran free wheat flour	wheat bran
Moisture	13.6	13.5	14
protein	14.51	14.25	16
Fat	1.6	0.85	2.76
Ash (total)	1.13	0.45	3.86
TDF	11	3.38	39.8
Wet gluten	n.a.	37	n.a.

TDF, Total Dietary Fiber; n.a.: not available.

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2 \right]^{1/2} \qquad [3]$$

Where, $MR_{exp.i}$ is the experimental moisture ratio at observation i, $MR_{pre,i}$ is the predicted moisture ratio at this observation, N is number of experimental data points, $\overline{MR}_{\exp}$ and $\overline{MR}_{pre}$ arethe average of sum of the$MR_{exp.i}$ and $MR_{pre,i}$, respectively.

Results and discussions

Flour chemical and Rheological properties

Bran free wheat flour and bran composition shown in table 2, As shown in table 2, the bran free wheat flour had lower dietary fiber in comparison with the bran. Rheological properties (Farinograph) of bran free wheat flour (85% extraction) was Water absorption (74), Dough development time(2.5 min), Mixing tolerance time(50 min) and Stability time (11.5 min).

Bran effect

The moisture content of the whole-wheat and bran free dough was 45.67 and 42.67% (w.b.), respectively. All the dough samples were dried until the final moisture content in crisp bread reached to 5±0.5% (w.b.). This moisture level is a critical value or standard value. The effect of bran on baking-drying process of the samples pointed via the changes in drying time. As shown in Fig. 1, the bran free samples had lower drying time in comparison with the whole-wheat samples. For instance, the bran free samples had approximately 65 min lower drying time than the whole-wheat samplesat 110 °C .

Temperature effect

As expected, increasing air temperature reduced greatly the baking-drying time (Figs. 2 and 3). At higher temperature, due to the quick removal of moisture, the baking-drying process occurred in a shorter period. The decrease in baking-drying time with increase in baking-drying temperature may be due to increase in water vapor pressure within the crisp bread, which increased the migration of moisture, especially when the baking-drying occurs only in falling rate period. Similar observation was reported for apple purees (Vergara *et al.*,1997).

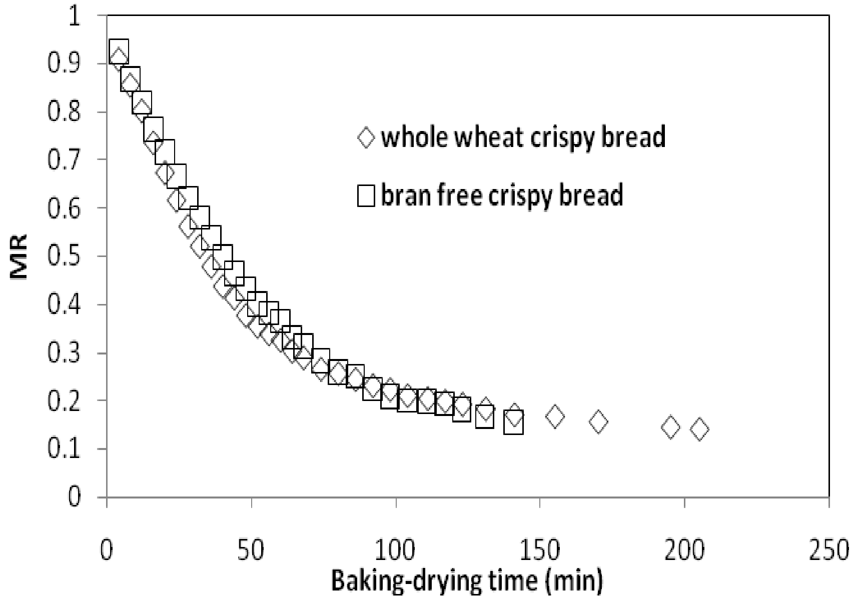

Fig. 1. Effect of bran on moisture ratio of crisp bread during baking-drying process at 110 °C.

The moisture ratio of crisp bread reduced exponentially as the baking-drying time increased. Continuous decrease in moisture ratio indicates that, diffusion governed the internal mass transfer (Haghi and Amanifard, 2008). In addition, higher baking-drying air temperature decreased the moisture ratio faster.During hot air baking-drying,the moisture content of crisp bread at all temperatures was brought to 5± 0.5% (w.b.). It is found that there was no constant rate baking-drying period in the baking-drying kinetics of crisp bread, and all baking-drying process occurred in the falling rate period (Fig. 4). This matter indicates that diffusion is the controlling physical mechanism regulating moisture transfer in the sample. The similar results were reported by Kaymak-Ertekin (2002) for green and red peppers, Sogi *et al.*, (2003) for tomato seeds and Doymaz (2007) for pumpkin.

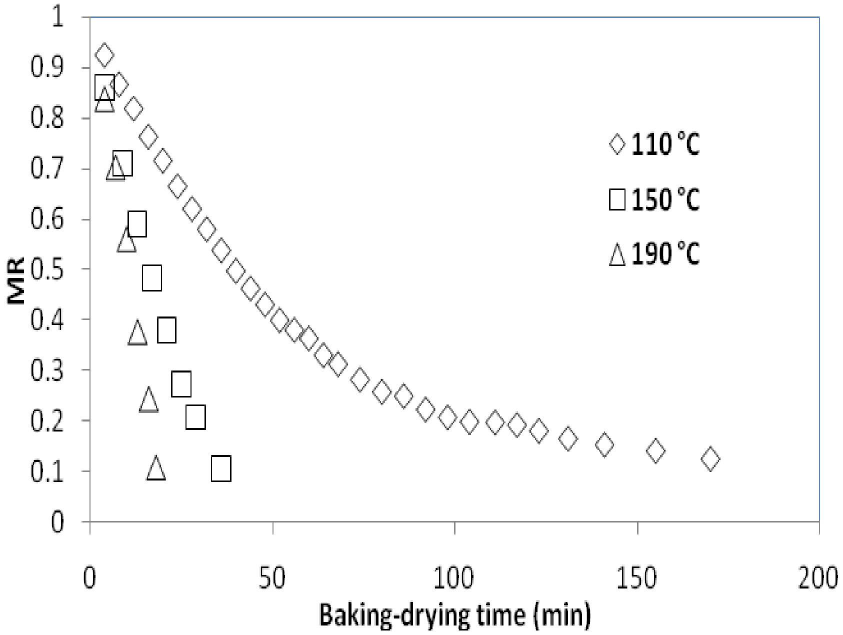

Fig. 2. Effect of baking-drying temperature on moisture ratio of bran free crisp bread.

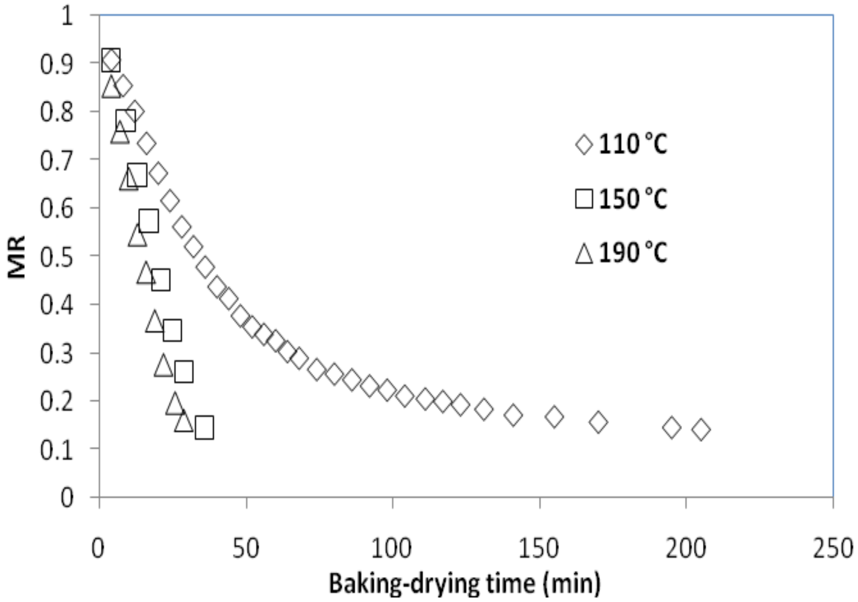

Fig. 3. Effect of baking-drying temperature on moisture ratio of whole-wheatcrisp bread.

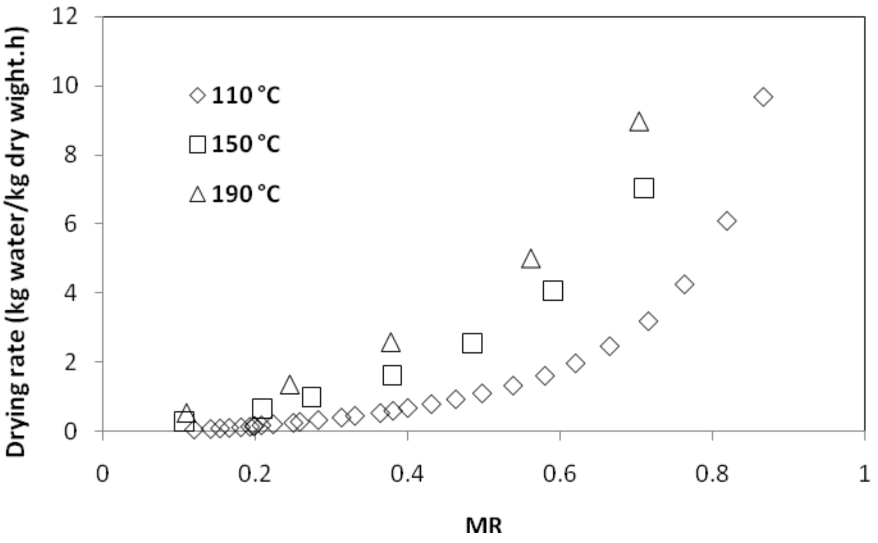

Fig. 4. Effect of baking-drying temperature on drying rate of bran free crisp bread.

Mathematical modeling

The moisture ratio-drying time values at each temperature were fitted using eight models given in Table 1 by applying the non-linear regression analysis technique.

The best model for each treatment was obtained using comparison of statistical parameters of $R^2$and RMSE. According to Table 3, for whole-wheat crisp bread, the Logarithmic, Page and Wang &Singh models were the best among the mathematical models used in fitting the experimental data at 110, 150 and 190°C, respectively. However, the results showed that the Logarithmic and Wang &Singh models predicted the closest data to the experimental data for bran free crisp bread baking- drying process at all selected temperatures (Table 4).

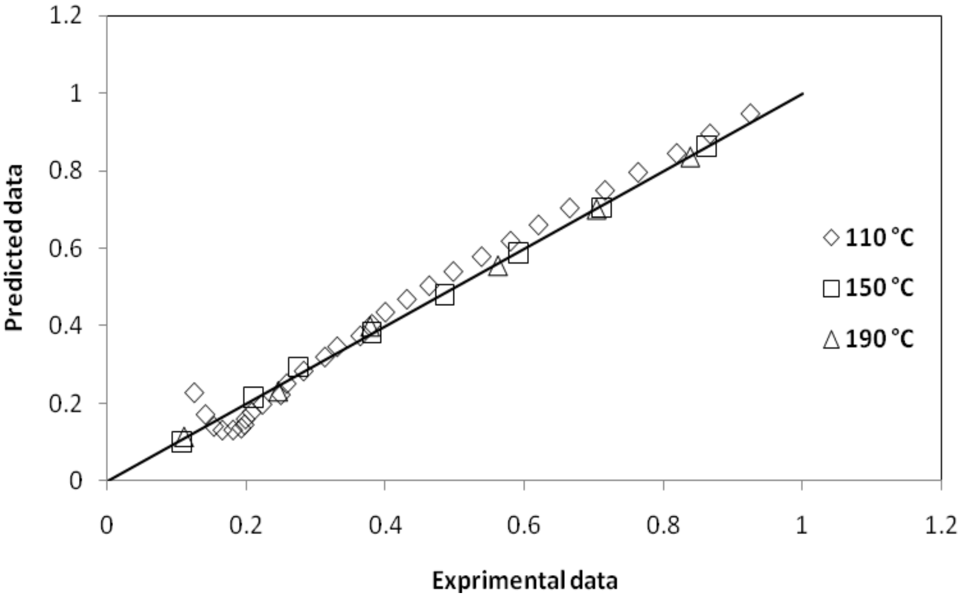

Fig. 5.Comparison of the experimental and predicted MR from Wang &Singhmodel for bran free crisp bread.

Table 3. Statistical results obtained from the selected models for whole wheat crisp bread

Model name	Temperature (°C)	R^2	RMSE
Newton	110	0.972	0.059
	150	0.984	0.057
	190	0.970	0.096
Page	110	0.974	0.036
	150	0.994	0.024
	190	0.987	0.030
Modified Page	110	0.972	0.059
	150	0.984	0.057
	190	0.970	0.096
Henderson &Pabis	110	0.955	0.052
	150	0.981	0.040
	190	0.948	0.060
Two- term	110	0.998	0.009
	150	0.981	0.040
	190	0.948	0.060
Logarithmic	110	0.998	0.009
	150	0.984	0.036
	190	0.948	0.017
Wang &Singh	110	0.937	0.080
	150	0.994	0.026
	190	0.998	0.013
Midilli et al.	110	0.996	0.014
	150	0.964	0.054
	190	0.991	0.028

Table 4. Statistical results obtained from the selected models for bran free crisp bread

Model name	Temperature (°C)	R^2	RMSE
Newton	110	0.992	0.027
	150	0.990	0.050
	190	0.970	0.096
Page	110	0.993	0.020
	150	0.996	0.016
	190	0.987	0.030
Modified Page	110	0.992	0.026
	150	0.990	0.049
	190	0.970	0.096
Henderson &Pabis	110	0.990	0.024
	150	0.983	0.036
	190	0.948	0.060
Two- term	110	0.990	0.024
	150	0.983	0.036
	190	0.948	0.060
Logarithmic	110	0.999	0.009
	150	0.997	0.014
	190	0.996	0.017
Wang &Singh	110	0.990	0.029
	150	0.998	0.011
	190	0.998	0.013
Midilli *et al.*	110	0.980	0.033
	150	0.991	0.012
	190	0.991	0.028

Figure 5 shows the good coincidence between experimental and predicted MR obtained from the best model at each baking-drying temperature for bran free crisp bread, which banded around the straight line (X=Y).It proved the feasibility of the selected model in describing the baking-drying behavior of the crisp bread.Soleimani Pour *et al.*, (2013) reported that Page model was the best mathematical model to describe baking of bread without any pretreatments in an electrostatic oven

Effective diffusivity

From the experimental data, internal mass transfer resistance was observed because of falling rate baking-drying period. Fick's diffusion equation analyzed the baking-drying data in the falling rate period. Crank (1975) solved this equation and introduced the following equation, whichcan be used for slab geometry with uniform initial moisture diffusion, constant diffusivity and insignificant shrinkage:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{4}$$

where, D_{eff} is the effective diffusivity (m^2/s); n is positive integer, t is drying time, and L is the half thickness of the slab in samples (m). In practice, only the first term inEq. (4) is used yielding:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{5}$$

As it is obvious, D_{eff} can be calculated from the slope of Eq. (5) using natural logarithm plot of MR versus baking-drying time.

The calculated D_{eff} values for two formulations at different baking-drying temperatures are shown in Fig. 6. It can be seen that the value of D_{eff} obtained for all crisp bread samples increased with increasing air temperature. This value for bran free crisp breadwas 2.88×10^{-8}, $8.26\times10^{-8}$and 1.11×10^{-7} m^2/s at110, 150 and 190 °C, respectively.. In addition, for whole-wheat crispy bread, this value was 2.47×10^{-8}, 5.27×10^{-8} and 8.84×10^{-8} m^2/s at 110, 150 and 190 °C, respectively. It is clear that the D_{eff} value for bran free crisp bread was more than that for whole-wheat crispy brad. Madamba *et al.* (1996) reported that the D_{eff} value for food materials is within the range of 10^{-11} to 10^{-9}. The obtained results were in agreement with the results of Kaleemullah and Kailappan (2005), Sacilik et al., (2006) and Doymaz (2007).

As the product temperature increase during baking, the moisture diffusivity at high baking temperatures increased exponentially. This may be attributed to the stimulated movement of water moleculeswith high temperatures and vapor formation that easeand quicken the moisture transport. As stated by Mizukoshi *et al.*, (1980), the starch gelatinization and the protein coagulation reactions take place during baking, at product temperatures of 80 °C and above. The structure of the crisp bread changes from a highly viscous dough to dry solid, leading higher moisture removal rate.

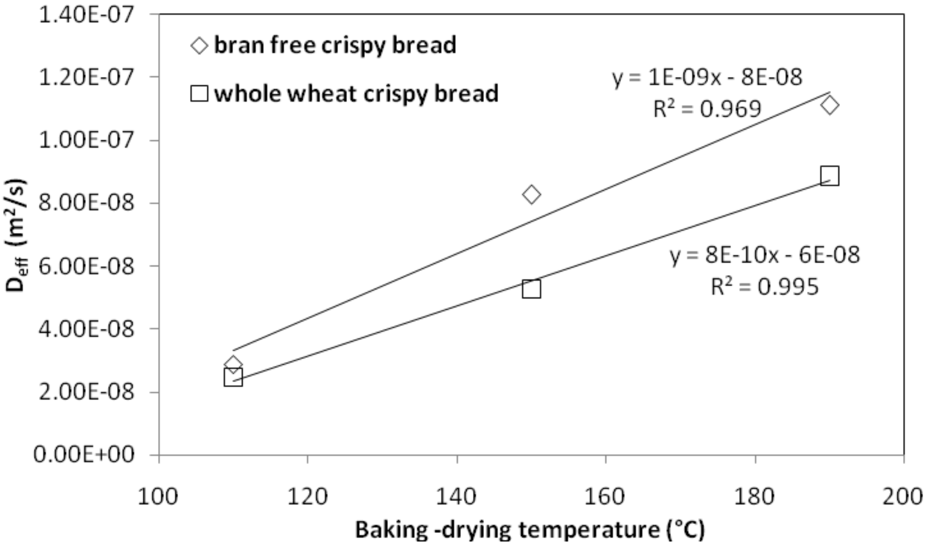

Fig. 6. Effect of baking-drying temperature on the effective moisture diffusivity in bran free and whole heat crisp bread.

Activation energy

From the Arrhenius-type relationship, the temperature dependence of D_{eff} can be explained (Simal *et al.*, 1996). This matter is shown in the following equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \qquad (6)$$

Where, D_0 is the pre-exponential factor of Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), T is the drying temperature (°C) and R is the gas constant (kJ/(mol.K)).

The E_a can be calculated from the slope of the plot on ln(D_{eff}) vs. 1/(T+273.15) (Fig. 8). This value was 25.22 and 23.43 (kJ/mol) for bran free and whole-wheat crisp bread, respectively. This obtained value was lower than the $E_a$of green peppers drying (51.4 kJ/ mol) (Kaymak-Ertekin, 2002), mint drying (82.93 kJ/mol) (Park et al., 2002). Baik and Marcotte (2002) reported a similar behavior; that is an exponential increase in the moisture diffusivity with increase the batter temperature.

Conclusion

In this study, baking-drying kinetics of whole-wheat and bran free crisp bread with 5±1 mm thickness at three levels of baking-drying temperatures in an electrostatic oven were investigated. Like most of food materials, crisp bread had not constant baking-drying rate process entirely occurred in falling rate period. High value of R^2 in addition with low value for RMSE obtained for Wang &Singh, Page and Logarithmic mathematical models indicated the high performance of these models to determine MR during the baking-drying process of the crisp breadat all temperatures. The effective moisture diffusivity of crisp bread was greatly affected by baking temperature and bran content.

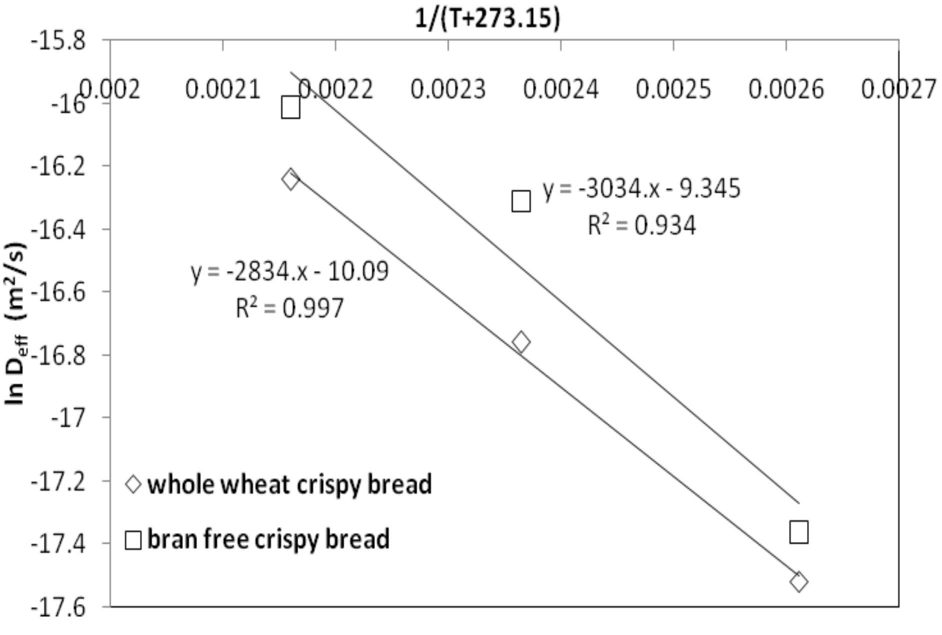

Fig. 7. Influence of baking-drying temperature on the effective diffusivity.

Furthermore, the effective diffusivity of whole-wheat and bran free crisp breads increased with increasing baking-drying temperature. The research shows that high moisture diffusivity for crisp bread drying can be achieved within a relatively short heating time. Both temperature and bran had significant influence on moisture diffusivity. The crisp bread moisture diffusivity had a positive relationship with temperature and improves moisture removal during cooling. Therefore, significant amount of moisture can be removed without additional energy consumption during cooling. The activation energy determined using Arrhenius-type equation for bran free and whole heat crisp bread was found to be 25.22 and 23.43 kJ/mol, respectively.

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Iranian Food Science and Technology Research Journal
Vol. 11, No. 3, Jul. Agu. 2015, p. 225-235

نشریه پژوهشهای علوم و صنایع غذایی ایران
جلد ۱۱، شماره ۳، مرداد - شهریور ۱۳۹۴، ص. ۲۳۵-۲۲۵

سنتیک پخت و خشک کردن نان خشک: تاثیر سبوس و دما

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تاریخ دریافت:۱۳۹۲/۰۷/۰۸
تاریخ پذیرش:۱۳۹۳/۰۳/۱۰

چکیده

در این پژوهش، مدل سازی ریاضی پختن و خشک کردن نان خشک به صورت لایه نازک مورد بررسی قرار گرفت. فرآیند خشک کردن لایه نازک در سه دمای مختلف ۱۱۰، ۱۵۰ و ۱۹۰ درجه سانتی گراد در سرعت هوای ۰/۵ ± ۰/۱ m/s رطوبت مطلق ۰/۶ ± ۰/۰۴ g/kg هوای خشک صورت گرفت. بر اساس یافته ها فرآیند پخت و خشک کردن در دوره نزولی اتفاق می‌افتد. انتقال رطوبت از نان خشک به وسیله مدل نفوذ فیک توصیف شد. نفوذ موثر در دامنه بین $۲/۸۸\times ۱۰^{-۸}$ تا $۱/۱۱\times ۱۰^{-۷}$ m^2/s برای نان خشک بدون سبوس و از $۲/۴۷\times ۱۰^{-۸}$ تا $۸/۸۴\times ۱۰^{-۸}$ m^2/s برای نان خشک حاصل از گندم کامل می‌باشد. انرژی فعال سازی برای نمونه‌ی بدون سبوس و نمونه گندم کامل به ترتیب ۲۲/۲۵ و ۲۳/۴۳ kj/mol می‌باشد که نشان دهنده تاثیر دما بر روی ضریب نفوذ است. هشت مدل معروف از مدل‌های پخت خشک کردن لایه نازک با داده های آزمایشگاهی و با استفاده از تکنیک آنالیز رگرسیون غیر خطی برازش شدند. براساس آنالیز آماری با استفاده از ظریب تبیین (R^2) و میانگین ریشه‌ی مربعات خطا (RMSE) بهترین مدل برای برازش داده های پخت و خشک کردن با هوای داغ نان خشک بدون سبوس، مدل وانگ و سینگ و لگاریتمی بود، در حالی که نمونه های نان خشک گندم کامل با مدل های پیج، لگاریتمی و وانگ و سینگ بهترین برازش را داشتند.

واژه‌های کلیدی: سبوس، نان خشک مسطح، خشک کردن، مدل های ریاضی، نان نازک، نفوذ موثر رطوبت، انرژی اکتیواسیون.

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