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Note

Determination of suitable drying curve model for bread moisture loss during baking

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A b s t r a c t. This study presents mathematical modelling of bread moisture loss or drying during baking in a conventional bread baking process. In order to estimate and select the appropriate moisture loss curve equation, 11 different models, semi-theoretical and empirical, were applied to the experimental data and compared according to their correlation coefficients, chi-squared test and root mean square error which were predicted by nonlinear regression analysis. Consequently, of all the drying models, a Page model was selected as the best one, according to the correlation coefficients, chi-squared test, and root mean square error values and its simplicity. Mean absolute estimation error of the proposed model by linear regression analysis for natural and forced convection modes was 2.43, 4.74%, respectively.

K e y w o r d s: moisture losing, bread, mathematical modelling

INTRODUCTION

Although people have practiced baking for a long time, the understanding of the whole process is not very clear. One of the possible reasons for this is that several fundamental complex physical processes are coupled during baking, like evaporation of water, volume expansion, gelatinization of starch, denaturation of protein, crust formation, *etc*. Several experimental and mathematical models have been developed for clear understanding of baking (Mondal and Datta, 2008).

As soon as the product is placed in the oven, water evaporates from the warmer region, absorbing latent heat of vaporization, and the surface layers start drying. Beneath this drying region, water vapour diffuses through the interconnected pores towards the surface, under the influence of the water vapour concentration gradient. A concomitant liquid water gradient is formed and ensures the diffusive transfer of water from the core to the surface. As the diffusive flow of liquid water from the core is less rapid than evaporation flow at the surface, a drying zone is developed which slowly increases in thickness and forms the crust.

Whereas bread crust is known to be closely related with moisture loss of bread during baking, the crust formation affects the amount of moisture evaporating from wet dough during the baking process as a thicker crust is produced with a higher moisture loss in bread (Mohd Jusoh *et al*., 2009; Wiggins, 1999). Besides that, moisture content or water activity of bread surface has an important effect on the beginning of the browning reactions. Purlis and Salvadori (2009) expressed that minimum requirements for the initiation of colour formation are temperature greater than 120°C and water activity less than 0.6. Also, in relating bread crust properties in terms of its colour with moisture loss, Purlis and Salvadori (2007) presented a strong correlation between the moisture loss and the crust colour formation in their study on browning kinetics of bread. From those reports, it seems viable to control moisture loss from bread during baking and to propose moisture loss models in order to predict bread moisture loss behaviour during baking.

Mathematical modelling using drying models has been studied in the drying of fruits, vegetables, seafood and other agriculture or crop products (Aghbashlo *et al*., 2009; Jain and Pathare, 2007; Thuwapanichayanan *et al*., 2008). The models fall into three categories, namely the theoretical, semi-theoretical and empirical (Akpinar *et al*., 2003). Examples of semi-theoretical models are such as the Newtonian model, Page model, Henderson and Pabis model, logarithmic model, two-term model, two term exponential model, Verma *et al*. (1985) model, and the Midilli-Kucuk model are used widely. In empirical modelling a direct relationship between the moisture content and drying time is derived (Akpinar, 2006). The Wang and Singh model is an example of empirical model used in literature.

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Newly, soft computing methods such as Artificial Neural Network (ANN) are widely used to modeling of drying processes (Gorjian *et al*., 2011; Karimi and Refiee, 2011), but mathematical modeling of the process is still important. So, the objective of the present study was to determine and test most appropriate drying model for understanding the moisture loss behaviour of bread samples during the baking process. In fact the moisture loss or the weight loss behaviour is effective in the formation of many characteristics of baked bread such as surface colour and crust thickness.

MATERIALS AND METHODS

Samples of bread dough were prepared using the straight dough method with the following ingredients formulation: wheat flour (100%), water (62.5%), sugar (1.5%), salt (1.5%) and dry yeast (1%). All the ingredients were mixed for 10 min in a home multi-function food processor. The dough was let to rest for 5 min after mixing. After first resting dough samples were formed by dividing and weighing the dough into 120 g cylinder dough balls and rounded with hand until uniform dough samples (*ca*. 0.15 m length and 0.025 diameter) were achieved and then let to rest for another 5 min. The prepared dough samples 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 the proving the volume of the samples was doubled.

Dough samples were baked in an electric static oven (Delongi EO1258, Italy) in two conditions of convection: natural convection (with 0 m s^{-1} air velocity) and forced convection (with 0.4 m s^{-1} air velocity). Three baking temperatures were selected for bread baking: 180, 200, 220°C. Oven temperature was measured using K-type thermocouples (Maxtermo-Gita, Taiwan). For better control of oven temperature a digital temperature controller was used as an additional mechanism. Therefore the oven temperature was controlled with high accuracy (approximately 1-2°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.

The theoretical and the semi-theoretical models are the most popular equations for the modelling of drying curve of agriculture products. These models relate the moisture ratio (*MR*) to the time of drying. The moisture ratio of bread samples during the baking experiments was calculated using the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e}, \quad (1)$$

where: M_t is the mean moisture content at time, t (% d.b.), M_0 is the initial moisture content (% d.b.), M_e is the mean equilibrium moisture content (% d.b.). Note should be taken that, for simplification, M_e in Eq. (1) was assumed to be zero, which was also assumed by some investigators (Arumuganathan, 2009; Guhan, 2005; Midilli and Kucuk, 2003).

Table 1. Values of the drying constants and coefficients of different models determined through regression method for bread samples at 180°C and natural convection

Model name	References	Model constants coefficients	R	χ^2	RMSE
Newton		k = 0.02261	0.9945	5.23 10^{-3}	0.0188
Page	Vega-Gálvez *et al*. (2010)	k = 0.01519, n = 1.111	0.9986	9.25 10^{-4}	0.0100
Henderson and Pabis	Aghbashlo *et al*. (2009)	a = 1.032, k = 0.02363	0.9975	2.55 10^{-3}	0.0134
Logarithmic		a = 1.15, c = -0.08146, k = 0.02065	0.9981	1.24 10^{-3}	0.0015
Two term		a = 1.059, b = -0.05868, k0 = 0.02447, k1 = 4.159	0.9982	1.25 10^{-3}	0.0032
Two-term exponential		a = 0.0003801, k = 59.44	0.9944	5.33 10^{-3}	0.0198
Wang and Sing	Arumuganathan *et al*. (2009)	a = -0.01979, b = 0.0001198	0.9977	7.26 10^{-3}	0.0126
Diffusion approach		a = 1.013, b = 0.7759, k = 0.02254	0.9945	5.26 10^{-3}	0.0206
Modified Henderson and Pabis	Aghbashlo *et al*. (2009)	a = 1.035, b = -0.2037, c = 0.1692, g = 0.2524, h = 0.159, k = 0.02394	0.9984	9.11 10^{-4}	0.0032
Verma *et al*. (1985)		a = 0.8095, g = 0.0234, k = 0.02243	0.9945	5.26 10^{-3}	0.0206
Midilli and Kucuk (2003)		a = 1.008, b = 0.001018, k = 0.01413, n = 1.167	0.9983	9.64 10^{-4}	0.0079

For mathematical modelling, 11 most popular drying equations (Table 1) were tested to select the best model for describing the moisture loss curve of the bread samples. The regression analysis was performed using the MATLAB computer program. In order to compare obtained results to determine the best fit, we used the correlation coefficient (R), chi-squared test (χ^2), and root mean square error analysis (RMSE).

Modelling the drying behaviour of different agricultural products often requires the statistical methods of regression and correlation analysis. Linear and non linear regression models are important tools to find the relationships between different variables, especially those for which no established empirical relationship exists. In this study, the relationships of the constants of the most suitable model with the drying air temperature were also determined by the linear regression technique model which is the most common mathematical expression. Finally, the performance of the proposed model was measured comparing experimental and predicted values. For this aim, the absolute relative error was defined as:

$$\varepsilon(\%) = \left[\frac{|MR\ predicted - MR\ experimental|}{MR\ experimental} \right]. \quad (2)$$

RESULTS AND DISCUSSION

Bread samples of 48% (w.b.) average initial moisture content were baked at temperatures of 180, 200 and 220°C in two modes of convection method *ie* natural convection ($V_a = 0$ m s^{-1}) and forced convection ($V_a = 0.4$ m s^{-1}), in an electric convective oven. All samples were placed in the baking oven for 60 min duration. Although, in various temperatures the time needed to obtain appropriate baking quality was different.

Figures 1and 2 illustrate the changes in the moisture ratio of the beard samples with baking time. It is clear from these figures that the moisture loss rate decreases continuously with the moisture content or baking time. There is no constant rate moisture loss period in these curves, and all the baking operations are seen to occur in the falling rate period. But, it can be seen that with the baking time the drying rate continuously tends to the constant drying rate period. As can be seen from Figs 1,2, one of the main factors influencing the moisture loss kinetics of bread samples is the oven temperature during the falling rate baking period. An increase in oven temperature resulted in a decrease in the baking time. The results were generally in agreement with some literature studies on the drying of various food products. According to Khazaei and Daneshmandi (2007), it is evident from these figures that the moisture content decreased continuously with the baking time and increasing oven temperature.

The moisture content data obtained for different oven temperatures and convection modes were converted to the moisture ratio expression, and then curve fitting computa-

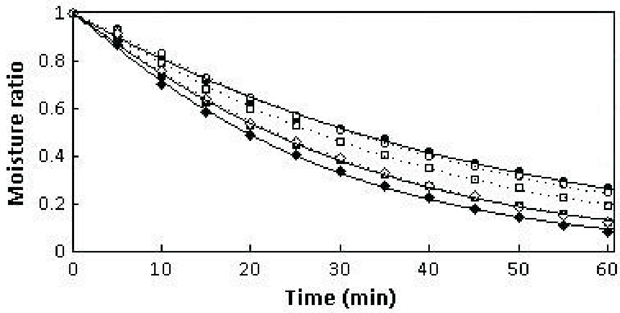

Fig. 1. Variation of the experimental and predicted moisture ratios by the Page model with baking time in both natural and forced convection mode (under natural convection (·····): ○180, □200, ◇220°C and under forced convection (—): ●180, ■ 200, ◆220°C.

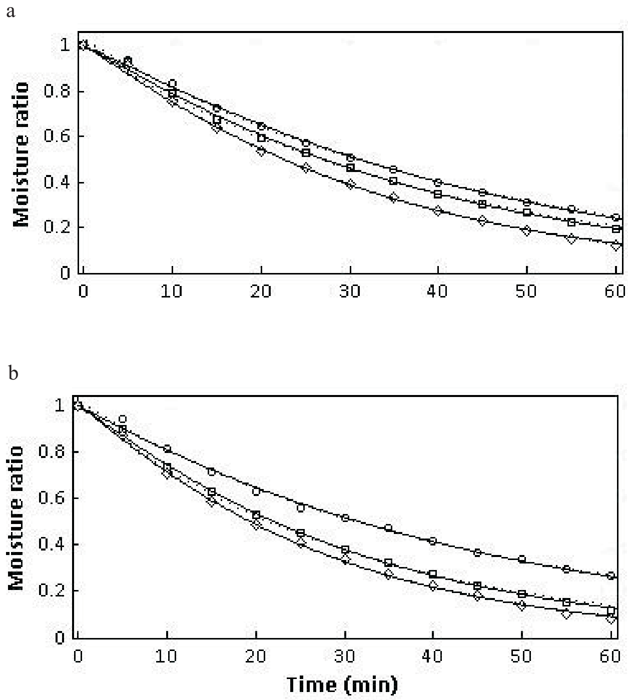

Fig. 2. Variation of the experimental and predicted moisture ratios by the Page model and Two-term model with baking time in: a – natural, b – forced convection modes (the Two-term model (….), the Page model (—). Explanations as in Fig. 1.

tions with the baking time were performed on the 11 drying models given by previous investigators (Table 1). The results of statistical analyses applied to these models at baking process at 180°C oven temperature and natural convection are given in Table 1. As can be seen from the statistical analysis results, generally high correlation coefficients are found for the drying models. Nevertheless, the results have shown that the highest values of R and the lowest values of reduced chi-squared and root mean square error could be obtained with the Page, Two-term and Midilli-Kucuk expressions. In this study, the Page model was preferred, due to its

T a b l e 2. Values of the drying constants and coefficients of the Page model determined through regression method for bread samples at all baking conditions

Baking temperature (°C)	Convection mode	k	*n*	R	χ^2	RMSE
180	natural	0.015	1.111	0.999	$9.25\ 10^{-4}$	0.0100
200	natural	0.017	1.120	0.998	$1.60\ 10^{-4}$	0.0124
220	natural	0.020	1.130	0.999	$1.17\ 10^{-4}$	0.0112
180	forced	0.022	1.075	0.997	$7.48\ 10^{-4}$	0.0156
200	forced	0.024	1.083	0.999	$8.63\ 10^{-5}$	0.0097
220	forced	0.027	1.095	0.999	$7.51\ 10^{-5}$	0.0090

n is the Page model coefficient.

simplicity, than two other models. Thus, the Page model may be assumed to represent the drying behaviour of bread samples (Table 1). The results of non-linear regression analyses and of statistical analyses applied to the Page model for all drying conditions are shown in Table 2. The results of the study presented in this paper are similar with earlier findings on drying of walnut (Hassan-Beygi *et al*., 2009) and bay leaves (Gunhan *et al*., 2005).

Further regression analyses were made to take into account the effect of the baking variables on the Page model constant (k). The effect of baking temperature, T (°C), and air velocity, V (m s^{-1}), on k was also included in the model by multiple regression analyses. The combinations of the variables that gave the highest R were finally covered in the final model. Based on the regression analyses, the accepted model constants and coefficients were as follows:

$$MR = \exp(-kt^n), \qquad (3)$$

where the model coefficients *ie n* and k were determined as function of baking temperature and air velocity:

$$k = 0.0001285\ T + 0.01742\ V - 0.008157 \quad R = 0.9791, \qquad (4)$$

$$n = 0.000474\ T - 0.09V + 1.025 \quad R = 0.9991. \qquad (5)$$

Using Eqs (4) and (5), the moisture contents of bread samples at any time during the baking process could be easily estimated. Validation of the established model was made by comparing the computed moisture contents with the measured moisture contents in any particular baking run under certain conditions. The performance of the model at all air temperatures and under natural (V_a = 0 m s^{-1}) and forced (V_a = 0.4 m s^{-1}) convections is shown in Fig. 3, respectively. It is obvious from these figures that the predicted data generally banded around the straight line, which indicated the suitability of the model proposed in describing the moisture losing behaviour of bread samples, as the mean relative errors produced by the model were 2.43% for natural convection mode and 4.74% for forced convection mode.

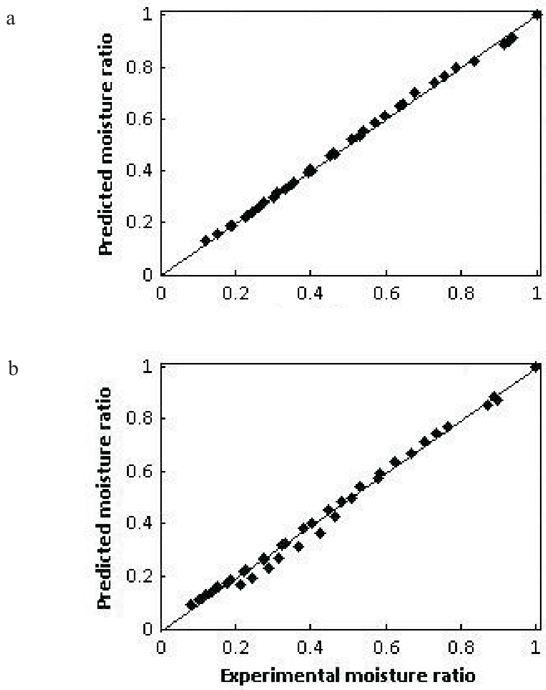

Fig. 3. Experimental and predicted moisture ratio in: a – natural and b – forced convection modes at all baking temperatures.

The prediction of baking performance of wheat sample is a difficult task as the mechanism of baking is not fully understood. From a transport phenomena point of view, bread baking has been considered as a simultaneous heat and mass transfer (SHMT) problem in a porous medium. It is very well known that thermophysical and dielectric properties of food depend very strongly on moisture content and temperature, especially for hygroscopic materials.

It has already been demonstrated that the development of crust browning depends mainly on oven temperature and has an experimental correlation with the weight loss during baking, and the crust is not a thermal insulation layer – rather it acts like a barrier towards weight loss as weight loss is a good representation of moisture variation at product surface during baking. Zanoni *et al*. (1993) reported a phenomenological model where the variation in temperature and water content of bread during baking is determined by the formation of an evaporation front at 100°C. The progressive advancing of this evaporation front towards the inside of the product results in the formation of two separate regions: the crust, where moisture is very low and temperature asymptotically tends to the oven temperature, and the crumb, where moisture is constant and temperature asymptotically tends to 100°C (Zanoni *et al*., 1994). In this way, only the external zones of bread suffer dehydration during baking; the development of the crust avoids the diffusion of internal water vapour in bread to the outside. In fact, with the crust formation in the initial minutes of baking, water evaporation from crumb section can be fully limited and moisture loss occur only at crust section. This phenomenon caused that bread crust thickness increased continually during baking and various baking temperature caused different rate of moisture loss from crust section and resulted in thickness of the crust.

As the results of this research showed, bread moisture loss during the baking process is similar to other food products and can be modelled and predicted by drying curve. Such models of bread moisture loss can be useful in many researches on bread characteristics and, since moisture loss can be measured more easily than other events occurring during baking, such as surface temperature, crust thickness, browning reactions of products and the like, and plays a vital role in bread baking, therefore the moisture loss model could be a main factor in modelling of the various bread baking aspects.

CONCLUSIONS

1. Mathematical modelling results showed that the drying curve models can be used to predict moisture loss behaviour of bread during baking.

2. Among the drying models, the Page model gave the best results and showed good agreement with the experimental data obtained from the experiments of the present study.

3. The linear regression on the constants and coefficients of the Page model for the effect of the oven temperature gave R = 0.981 in natural convection mode and R = 0.958 in forced convection mode for bread samples.

4. The mean relative errors produced by the moisture ratio predicting model were 2.43% for natural convection mode and 4.74% for forced convection mode.

5. The Page model adequately explained the moisture losing behaviour of bread at a temperature range of 180-220°C and under both natural and forced convection mode.

REFERENCES

Ayensu A., 1997. Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy, 59, 121-126.

Aghbashlo M., Kianmehr M.H., Khani S., and Ghasemi M., 2009. Mathematical modelling of thin-layer drying of carrot. Int. Agrophys., 23, 313-317.

Akpinar E.K., 2006. Determination of suitable thin layer drying curve model for some vegetables and fruits. J. Food Eng., 73, 75-84.

Akpinar E.K., Bicer Y., and Yildiz C., 2003. Thin layer drying of red pepper. J. Food Eng., 59, 99-104.

Arumuganathan T., Manikantan M.R., Rai R.D., Anandakumar S., and Khare V., 2009. Mathematical modeling of drying kinetics of milky mushroom in a fluidized bed dryer. Int. Agrophys., 23, 1-7.

Gorjian S., Tavakkoli Hashjin T., and Khoshtaghaza M.H., 2011. Designing and optimizing a back propagation neural network to model a thin-layer drying processes. Int. Agrophys., 25, 13-19.

Gunhan T., Demir V., Hancioglu E., and Hepbasli A., 2005. Mathematical modeling of drying of bay leaves. Energy Conv. Manag., 46, 1667-1679.

Hassan-Beygi S.R., Aghbashlo M., Kianmehr M.H., and Massah J., 2009. Drying characteristics of walnut (*Juglans regia* L.) during convection drying. Int. Agrophys., 23, 129-135.

Henderson S.M., 1974. Progress in developing the thin layer drying equation. Trans. ASAE, 17, 1167-1178.

Jain D. and Pathare P.B., 2007. Study the drying kinetics of open sun drying of fish. J. Food Eng., 78, 1315-1319.

Karimi F. and Rafiee S., 2011. Optimization of air drying process for lavender leaves. Int. Agrophys., 25, 229-239.

Khazaei J. and Daneshmandi S., 2007. Modeling of thin-layer drying kinetics of sesame seeds: mathematical and neural networks modeling. Int. Agrophysics, 21, 335-348.

Midilli A. and Kucuk H., 2003. Mathematical modelling of thin layer drying of pistachio by using solar energy. Energy Conversion Manag., 44, 1111-1122.

Mohd Jusoh Y.M., Chin N.L., Yusof Y.A., and Abdul Rahman R., 2009. Bread crust thickness measurement using digital imaging and L a b colour system. J. Food Eng., 94, 366-371.

Mondal A. and Datta A.K., 2008. Bread baking – A review. J. Food Eng., 86, 465-474.

Purlis E. and Salvadori V.O., 2007. Bread browning kinetics during baking. J. Food Eng., 80, 1107-1115.

Purlis E. and Salvadori V.O., 2009. Modelling the browning of bread during baking. Food Res. Int., 42, 865-870.

Thuwapanichayanan R., Prachayawarakorn S., and Soponronnarit S., 2008. Drying characteristics and quality of banana foam mat. J. Food Eng., 86, 573-583.

Vega-Gálvez A., Miranda M., Diaz L.P., Lopez L., Rodruguez K., and Di Scala K., 2010. Effective moisture diffusivity determination and mathematical modelling of the drying curves of the olive-waste cake. Biores. Technol., 101, 7265-7270.

Verma L.R., Bucklin R.A., Endan J.B., and Wraten F.T., 1985. Effects of drying air parameters on rice drying models. Trans. Am. Soc. Agric. Eng., 28, 296-301.

Wiggins C., 1999. Proving, baking, cooling. In: Technology of Breadmaking (Eds S.P. Cauvain, L.S. Young). Aspen Publishers, Maryland.

Yaldiz O. and Ertekin C., 2001. Thin layer solar drying of some vegetables. Drying Technol., 19, 583-596.

Zanoni B., Peri C., and Pierucci S., 1993. A study of the bread-baking process. I: a phenomenological model. J. Food Eng., 19, 389-398.

Zanoni B., Pierucci S., and Peri C., 1994. Study of the bread baking process. II: mathematical modelling. J. Food Eng., 23, 321-336.