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Investigation of Drying Characteristics of Parboiled Wheat Kernel in a Halogen Lamp Dryer and Its Modelling

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Abstract

In this study, the halogen drying characteristics of parboiled wheat was investigated. Drying experiments were performed at different temperatures (50, 60, 70 and 80 °C) and selected thin layer drying models were applied to drying data. The effects of drying temperature on drying rate, drying rate constant and effective diffusivity of parboiled wheat were evaluated. It was observed that the drying occurred in the falling rate period and the drying constant increased with increasing of drying temperature. Weibull distribution model among the using mathematical models was the best mathematical model representing the drying curves. Effective moisture diffusivity was calculated using the Fick's second law and varied from 6.39×10^{-11} to 2.22×10^{-10} m^2 s^{-1} over the temperature range. The temperature dependency of effective diffusion coefficient was correlated by the Arrhenius-type relationship. Activation energy (E_a) was determined as 39.667 kJ $gmol^{-1}$.

Keywords: Halogen drying, mathematical modelling, parboiled wheat kernel, thin-layer drying

Halojen Lambalı Bir Kurutucuda Haşlanmış Buğdayın Kuruma Karakteristiğinin İncelenmesi ve Modellenmesi

Özet

Bu çalışmada, haşlanmış buğdayın halojen kurutma karakteristiği incelendi. Kurutma deneyleri 50, 60, 70 ve 80 °C sıcaklıklarında gerçekleştirildi ve elde edilen deneysel verilere seçilmiş ince tabaka kuruma modelleri uygulandı. Haşlanmış buğdayın kuruma hızı, kuruma hız sabiti ve etkin difüzyonu üzerine kurutma sıcaklığının etkisi değerlendirildi. Kuruma olayının azalan hız periyodunda gerçekleştiği ve kuruma hız sabitinin artan sıcaklıkla arttığı görüldü. Kullanılan modeller arasında Weibull distribution modelinin kuruma eğrilerini temsil eden en iyi model olduğu belirlendi. Etkin nem difüzyon katsayısı Fick'in ikinci kanunundan hesaplandı ve çalışılan sıcaklık bölgesinde 6.39×10^{-11}-2.22×10^{-10} m^2 s^{-1} aralığında değiştiği belirlendi. Etkin difüzyon katsayısının sıcaklıkla ilişkisi Arrhenius tipi ilişki ile ifade edildi. Aktivasyon enerjisi (E_a) 39.667 kJ $gmol^{-1}$ olarak belirlendi.

Anahtar kelimeler: Halojen kurutma, matematiksel modelleme, haşlanmış buğday, ince tabaka kurutma

INTRODUCTION

Wheat is one of the most important sources of complex carbohydrates have an important role in human nutrition. Amount of wheat produced in 2014 is about 729 million tonnes and 19 million tonnes in the world and Turkey, respectively (URL-1, 2016). Wheat flour is the most important ingredient in home baking and is the framework for almost every commercial baked product and pasta. The main stages of wheat flour production are separation, tempering, drying and grinding. Tempering stage is known as "parboiling treatment" and obtained parboiled wheat kernel from this stage is dried until about 12 % moisture content before grinding stage (Kahyaoglu et al., 2010).

Drying is of fundamental importance in most sectors of food processing and one of the oldest methods of food preservation. Drying can be described in simple terms as removing water from a wet/moist material. However, drying is a complex process of heat and mass transfer between the moist material and its environment (Midilli et al., 2002).

Contact, convective, radiative and freeze drying are applied methods for drying of food and agricultural materials (Yagcıoglu et al., 1999). Open sun drying as traditional is the most common method used to preserve agricultural products. However, this weather dependent technique has also contamination problems. Hot air drying has long drying time during the falling rate period due to its

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low energy efficiency (Toğrul, 2006). Infrared (IR), drying is an effective method for moisture removal. Energy obtained from IR heating element is transferred to the product surface without heating the surrounding air. The radiation bumps on the subjected material and penetrates it and then is converted to sensible heat (Ginsburg, 1969). Infrared radiation can also be used to supply latent heat of water evaporation. Infrared energy is absorbed by surface layers to a depth and the absorption ability depends on the kind of heated material (Lewicki, 2006). Because surrounding air is practically not heated, the infrared energy is delivered directly to the dried material. Therefore, drying time in infrared drying process is reduced compared to the convective drying (Nowak and Lewicki, 2004). Infrared drying has many advantages such as uniform heating, high heat transfer rate, reduced drying time and energy uptake and improved product quality. Because of these advantages compared hot air drying, popularity of infrared drying in food processing is enhanced (Vishwanathan et al., 2013). Halogen drying is up to twice as fast as traditional infrared technology (drying time may vary depending on substance type). Halogen operating advantages are more efficient than other methods because of the technology of small intense heating elements used as the substrate for the thermoradiator. Al-Hilphy and AlRikabi (2013) investigated the drying kinetics behaviour of strawberry as experimental by using the halogen dryer at temperature level 60, 70 and 80 °C.

Thin-layer drying kinetics of wheat kernel was investigated by various researchers; for example, hot-air convective dryer (Watson and Bhargava, 1974; Mohapatra and Rao, 2005; Kalender and Akosman, 2012), microwave assisted spouted bed dryer (Kahyaoglu et al., 2010).

Although extensive work has been done on drying of wheat and its derivative as bulgur, limited literature is available on halogen lamp dryer characteristics of parboiled wheat. Therefore, the objectives of this study were (1) to investigate the halogen lamp dryer kinetics of the parboiled wheat to evaluate the effect of drying temperature on drying process, (2) to evaluate a suitable model for describing the drying process and to estimate the constant of selected thin-layer model equations, (3) to determine the effect of temperature on diffusion coefficient and activation energy.

MATERIAL AND METHOD

Material

Wheat sample (*Triticum aestivum* L.) called KIRAC-66 used in this study was procured from a local market. Wheat sample was parboiled at water/solid mass ratio of 3/1 for 1 hour. Parboiled wheat sample was filtered and then stored in polyethylene bags. The initial moisture content of wheat sample and parboiled wheat samples was determined as about 10 and 40 % (wet basis) by standard oven method (AOAC, 1985), respectively.

Experimental Setup and Method

In this study, it was used a drying equipment (A&D MX-50, Japan) with halogen lamp which is maximum power of 400 W (Figure 1). The drying experiments were conducted at 50, 60, 70 and 80 °C and replicated three times at each temperature. Mass changes of parboiled wheat samples were recorded with the aid of a computer at 5 min interval in each drying temperature. Moisture content (MC), dimensionless moisture ratio (MR) and drying rate (DR) were determined using the following equations:

$$MC=\frac{w_t - w_d}{w_d} \quad (1)$$

$$MR=\frac{M_{C_t} - M_{C_e}}{M_{C_0} - M_{C_e}} \quad (2)$$

$$DR=\frac{M_{C_{t+dt}} - M_{C_t}}{dt} \quad (3)$$

Where; w_t (g) and w_d (g) are the masses of the wheat samples at any time of drying and at the end of drying, respectively. M_{C_0} ($g_{water}\ g_{dm}^{-1}$) and M_{C_t} ($g_{water}\ g_{dm}^{-1}$) are the moisture contents of the wheat samples in the beginning and at any time of drying, respectively. M_{C_e} ($g_{water}\ g_{dm}^{-1}$) is the equilibrium moisture content. It has been regarded as the moisture content at the end of drying in the infrared drying (Toğrul, 2006). *DR* ($g_{water}\ g_{dm}^{-1}\ min^{-1}$) and dt (min) are the drying rate and the period between two consecutive measurements, respectively.

Mathematical Modelling of Drying Curves

Five mathematical models in the literature were used in this study (Table 1). The constants of the mathematical models were determined by doing regression analysis. Regression analyses were done with Statistica data analysis program (version 10). The consistency between the moisture ratios that were determined experimentally and calculated from the mathematical model was determined by

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Table 1. Mathematical models for drying of parboiled wheat

Model No	Model name	Model equation	Reference
1	Logarithmic	$MR = a\,exp(-k\,t) + c$	Yaldız and Ertekin, 2001
2	Diffusion Approach	$MR = a\,exp(-k\,t) + (1-a)\,exp\,(-k\,b\,t)$	Doymaz, 2013
3	Two-Term	$MR = a\,exp(-k_0\,t) + b\,exp\,(-k_1\,t)$	Arslan and Özcan , 2010
4	Henderson & Pabis	$MR = a\,exp\,(-k\,t)$	Yagcıoglu et al., 1999
5	Weibull Distribution	$MR = a - b\,exp\,(-(k\,t^n))$	Corzo et al., 2008

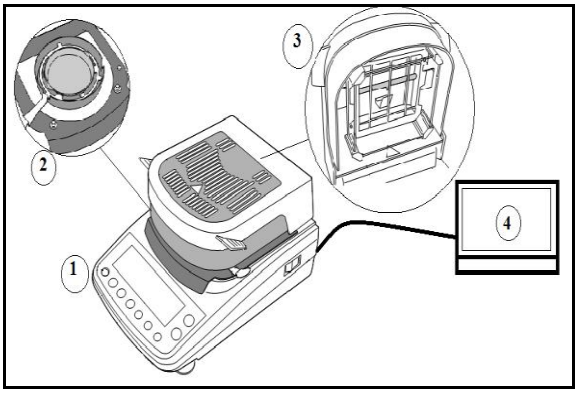

Figure 1. Experimental setup. (1) A&D MX-50 halogen lamp dryer, (2) sample pan, (3) halogen radiator and temperature sensor, (4) computer (original)

using statistical parameters, i.e. determination of coefficient (R^2), chi-square (χ^2), root mean square error (*RMSE*), and percentage error (*E %*). Small χ^2 and *RMSE* values and high R^2 values show that the model was more suitable (Yaldız and Ertekin, 2001; Midilli and Kucuk, 2003). The *E* % values smaller than 10 % were acceptable (Park et al., 2002).

The values of χ^2, *RMSE* and *E* % were calculated with the following equations.

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp,\,i} - MR_{pre,\,i})^2}{N-n} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (MR_{exp,\,i} - MR_{pre,\,i})^2}{N}} \quad (5)$$

$$E\,\% = \frac{100}{N} \sum_{i=1}^{N} \frac{|MR_{exp,\,i} - MR_{pre,\,i}|}{MR_{exp,\,i}} \quad (6)$$

Where; $MR_{exp,\,i}$ is the experimental moisture ratio at *i* th observation, $MR_{pre,\,i}$ is the predicted moisture ratio for this observation, *N* is the number of observations and *n* is the number of constants in the model.

Diffusion of Moisture and Activation Energy

The effective diffusion coefficient for the wheat kernels was determined by using Fick's diffusion equation. The solution of Fick's second law in spherical geometry was as follows (Crank, 1975):

$$MR = \frac{M_{C_t} - M_{C_e}}{M_{C_0} - M_{C_e}} = \frac{6}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{i^2}\, exp\left(-i^2 \cdot \frac{\pi^2 \cdot D_{eff}}{r^2} \cdot t\right) \quad (7)$$

For long drying periods, the Eq. (7) can be simplified (i.e. for *i*=0) and then can be written in logarithmic form:

$$ln(MR) = ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 \cdot D_{eff}}{r^2} \cdot t\right) \quad (8)$$

Where; *t* (s) is time, *r* (m) is equivalent radius, 2.21 10^{-3} m, of a single parboiled wheat, D_{eff} ($m^2\,s^{-1}$) is the effective diffusion coefficient. Experimental *ln (MR)* values and drying time can be transferred onto a graph and the effective diffusion coefficient is calculated from the slope (Eq. (8)) of line obtained from the graph.

$$Slope = \frac{\pi^2 \cdot D_{eff}}{r^2} \quad (9)$$

Temperature dependence of the effective diffusion coefficient is generally expressed by Arrhenius Equation as Eq. (10).

$$D_{eff} = D_0\, exp\left(-\frac{E_a}{R \cdot T}\right) \quad (10)$$

Where; D_0 is diffusivity at infinite high temperature, E_a (kJ $gmol^{-1}$) is the activation energy and R (J $gmol^{-1}\,K^{-1}$) is the universal gas constant, 8.314.

RESULTS AND DISCUSSION

Drying Behaviour

Wheat samples were dried at 50, 60, 70 and 80 °C of drying temperatures in order to determine the effect of temperature on drying characteristics of wheat. The change of the moisture ratio with drying times at different temperatures was shown in Figure 2. It was seen that moisture ratio decreased exponentially with time. It was reached the final moisture ratio after periods of 161, 155, 115 and 110 minutes at 50, 60, 70 and 80 °C, respectively.

The change in drying rates with time and moisture content at different temperatures was shown in Figure 3 and Figure 4, respectively. The falling rate period was seen from drying curves. It

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was seen that drying rate was increased with an increase in drying temperature. This result shows that the mechanism governing moisture movement is diffusion in halogen lamp drying.

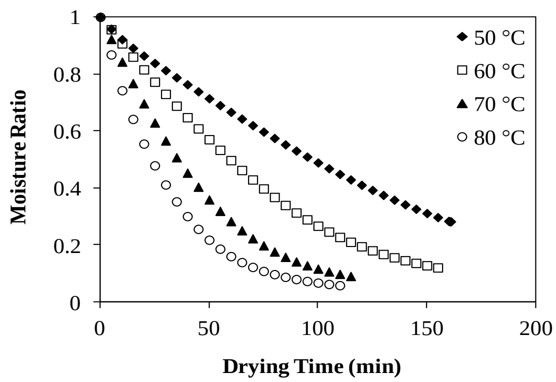

Figure 2. Drying curves of parboiled wheat samples at different temperatures

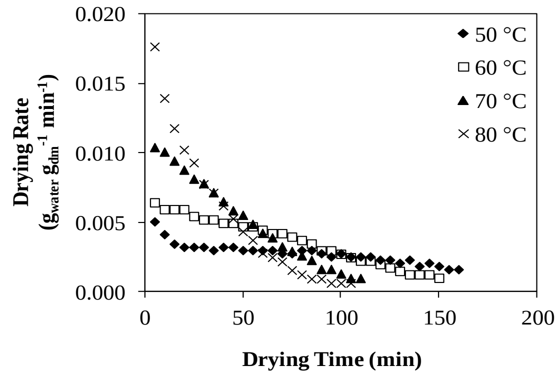

Figure 3. Drying rates of parboiled wheat samples versus drying time at different temperatures

Modelling of Drying Data

Five thin layer drying models were used to describe drying characteristics of parboiled wheat in the halogen lamp dryer. Model constants and coefficients of mathematical models used are presented in Table 2. Generally, in almost all of the drying models, as the drying temperature increased, drying rate constant (k) increased as well.

The statistical analysis results for mathematical models are summarised in Table 3. All the five models, obtained R^2 is greater than 0.99, which is in the acceptable range for all the drying temperatures. R^2, *RMSE*, χ^2 and *E %* values ranged from 0.9947 to 0.9999, 0.0026 to 0.0191, 0.6686×10^{-5} to 37.0313×10^{-5}, and 0.4394 to 7.0444, respectively. As the statistical analysis result, it was observed that Weibull Distribution Model was the best mathematical model representing the drying behaviour of the parboiled wheat kernel at all drying temperatures.

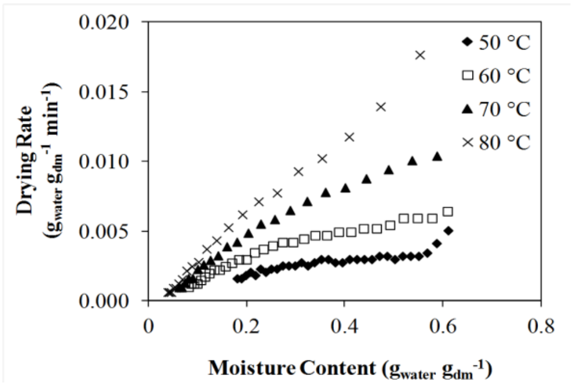

Figure 4. Drying rates of parboiled wheat samples versus moisture content at different temperatures

Diffusion Coefficient and Activation Energy

Fick's second law in spherical geometry was used to describe the drying behaviour of wheat kernel samples. The change of the *ln MR* with drying times at different temperatures was shown in Figure 5. It was seen that drying behaviour is compatible with Eq. (8). From the slope of lines, values of effective diffusion coefficients (D_{eff}) were calculated as 6.39×10^{-11}, 1.18×10^{-10}, 1.81×10^{-10} and 2.22×10^{-10} m^2 s^{-1} for drying temperatures of 50, 60, 70 and 80 °C, respectively. It was observed that the effective diffusivity increased with the increase of the drying temperatures.

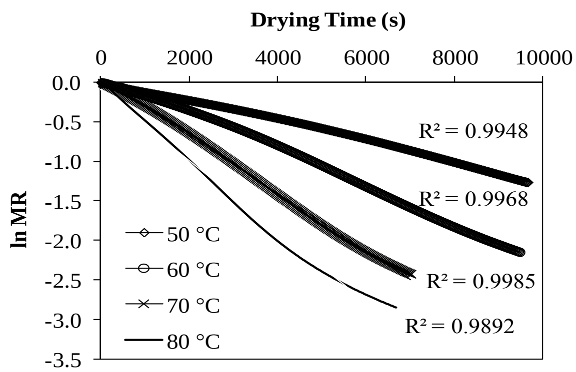

Figure 5. Changes of the *ln MR* with drying time at different temperatures

The moisture diffusivity was plotted against the reciprocal of absolute drying temperature in Figure

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Table 2. Constants and coefficients of the models used at different temperatures

Temperature (°C)	*Model No*	*Constants and coefficients*			
50	1	a=1.4394	k=0.0042	c=-0.4536	-
	2	a=0.9718	k=0.0073	b=1.0004	-
	3	a=0.6679	k_0=0.0074	b=0.3457	k_1=0.0074
	4	a=1.0136	k=0.0074	-	-
	5	a=-0.6059	k=0.0044	b=-1.5957	n=0.9676
60	1	a=1.1604	k=0.0103	c=-0.1329	-
	2	a=2.3649	k=0.0183	b=1.3934	-
	3	a=0.6672	k_0=0.0133	b=0.3909	k_1=0.0133
	4	a=1.0581	k=0.0133	-	-
	5	a=0.0180	k=0.0045	b=-0.9663	n=1.2353
70	1	a=1.0665	k=0.0197	c=-0.0357	-
	2	a=18.7792	k=0.0132	b=0.9754	-
	3	a=1.1505	k_0=0.0231	b=-0.1535	k_1=0.0830
	4	a=1.0438	k=0.0214	-	-
	5	a=0.0357	k=0.0104	b=-0.9532	n=1.1865
80	1	a=0.9964	k=0.0319	c=0.0215	-
	2	a=0.9999	k=0.0299	b=-1.7847	-
	3	a=1.4064	k_0=0.0298	b=-0.4021	k_1=0.0298
	4	a=1.0043	k=0.0298	-	-
	5	a=0.0346	k=0.0255	b=-0.9634	n=1.0654

Table 3. Statistical results for models used

Temperature (°C)	*Model No*	*Parameter*			
		R^2	*RMSE*	*χ^2 x 10^5*	*E %*
50	1	0.9998	0.0032	1.0284	**0.4394**
	2	0.9947	0.0149	22.4168	2.7374
	3	0.9954	0.0139	19.6347	2.5015
	4	0.9954	0.0139	19.5124	2.5013
	5	**0.9998**	**0.0031**	**0.9796**	0.4856
60	1	0.9985	0.0104	10.8650	3.2655
	2	**0.9998**	**0.0041**	**1.7157**	1.3608
	3	0.9948	0.0191	37.0313	5.5068
	4	0.9948	0.0191	36.7961	5.5077
	5	0.9997	0.0044	1.9694	**1.1704**
70	1	0.9988	0.0092	8.6067	3.4851
	2	0.9982	0.0113	12.9960	4.3752
	3	0.9998	0.0040	1.6109	1.8591
	4	0.9982	0.0115	13.2613	3.1861
	5	**0.9999**	**0.0026**	**0.6686**	**0.8458**
80	1	0.9996	0.0054	3.0028	3.2472
	2	0.9997	0.0048	2.3642	2.3006
	3	0.9988	0.0090	8.1786	7.0444
	4	0.9988	0.0090	8.1049	7.0444
	5	**0.9998**	**0.0040**	**1.6366**	**1.7780**

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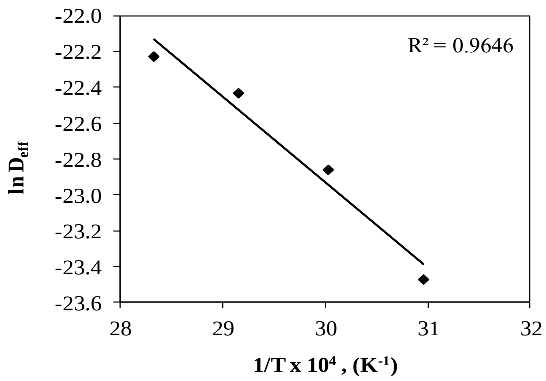

Figure 6. Arrhenius type relationship between effective moisture diffusivity and temperature

6. The slope of the straight line in Figure 6 gives the *-Ea/R*. From the value of this slop, the activation energy *(E_a)* was calculated as 39.667 kJ gmol^{-1}. This value was determined as 37.013 kJ gmol^{-1} at forced convective dryer conditions by Mohaparta and Rao (2005).

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