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The thin layer drying characteristics of hazelnuts during roasting

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Abstract

Thin layer drying characteristics of hazelnuts during roasting were described for a temperature range of 100–160°C, using five semi-theoretical and two empirical thin layer models. The effective diffusivity varied from 2.301×10^{-7} to 11.759×10^{-7} m^2/s over the temperature range. Temperature dependence of the diffusivity coefficient was described by Arrhenius-type relationship. The activation energy for moisture diffusion was found to be 1891.6 kJ/kg. Thin layer drying characteristics of hazelnut roasting were satisfactorily described by an empirical Thompson model with the linear temperature dependence. © 2000 Elsevier Science Ltd. All rights reserved.

Notation

a, a_1, a_2	drying constant
b, b_1, b_2	drying constant
C	coefficient
db	dry basis
D	effective diffusivity (m^2/s)
D_o	diffusivity coefficient
E_a	activation energy (kJ/kg)
k, k_1, k_2	drying constant
MC	moisture content
MR	moisture ratio ($M - M_e/M_o - M_e$)
n	drying constant, number of observations
P	mean relative deviation modulus (%)
R^2	correlation coefficient
R	Universal gas constant, radius
t	time (min)
T	temperature

Subscripts

a	absolute
e	equilibrium
i	ith observation
o	initial
pr	predicted

1. Introduction

Turkey is the main hazelnut producer of the world with amounts of about 600 000 tonnes per year, followed by Italy, USA, and Spain. Total export revenue of Turkey from hazelnut and hazelnut products is about one billion US dollars annually (Özdemir & Devres, 1999). Like other nuts and beans, roasting is one of the common form of processing hazelnuts. Roasting alters and significantly enhances the flavour, colour, texture and appearance of nuts. The resulting product is delicate, uniquely nutty and widely enjoyed compared to raw nuts. Roasting also removes pellicle of hazelnut kernels, inactivates enzymes that speed up nutrient damage and destroys undesirable microorganisms and food contaminants (Buckholz, Daun & Stier, 1980; Mayer, 1985; Moss & Otten, 1989; Sanders, Vercelotti, Blankenship, Crippen & Civille, 1989; Jayalekshmy & Mathew, 1990; Pattee, Giesbrecht & Isleib, 1995; Hashim & Chaveron, 1996; Köksal & Okay, 1996; Perren & Escher, 1996a,b; Perren, Handchin & Escher, 1996a,b; Richardson & Ebrahem, 1996; Shimoda, Nakada, Nakashima & Osijima, 1997; Jung, Bock, Back, Lee & Kim, 1997; Jinap, Wan-Rosli, Russly & Nordin, 1998; Atakan & Bostan, 1998). In order to improve quality of roasted hazelnut products, it is necessary to understand these physical, biochemical and microbial changes during roasting. Drying is one of the processes occurring during roasting operation and is related with textural changes during roasting (Mayer, 1985; Perren & Escher, 1996a,b).

Drying/roasting of foods depends on the heat and mass transfer characteristics of the product being dried. A knowledge of temperature and moisture distribution in the product is vital for equipment and process design,

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quality control, choice of appropriate storage and handling practices. Mathematical models that describe drying mechanisms of foods can provide the required temperature and moisture information (Parry, 1985; Parti, 1993). Among mathematical models, thin layer drying models have been found wide application due to their ease of use and lack of required data in complex theoretical models (such as phenomenological and coupling coefficients) (Madamba, Driscoll & Buckle, 1996). Isothermal conditions within the grain, but not with time are assumed in thin layer drying models due to the fact that the rate of heat equalisation within the grain is two orders of magnitude greater than the rate of moisture equalisation. Therefore only moisture diffusion is used to describe mass transfer in the medium (Whitaker, Barre & Hamdy, 1969; Young, 1969). Thin layer drying models fall into three categories namely, theoretical, semi-theoretical and empirical. The first takes into account only internal resistance to moisture transfer while the other two consider only external resistance to moisture transfer between product and air (Henderson, 1974; Whitaker et al., 1969; Fortes & Okos, 1981; Bruce, 1985; Parti, 1993). The most widely investigated theoretical drying model has been Fick's second law of diffusion (see Table 1). Drying of many food products such as rice (Ece & Cihan, 1993) and hazelnut (Demirtaş, Ayhan & Kaygusuz, 1998), soybean (Suarez, Viollaz, & Chirife, 1980a), rapeseed (Crisp & Woods, 1994), pistachio kernel (Karataş & Battalbey, 1991) has been successfully predicted using Fick's second law with Arrhenius-type temperature dependent diffusivity. Nevertheless, many assumptions necessarily required to use this law to describe falling-rate drying period of foods have been proven to be invalid (Moss & Otten, 1989).

Semi-theoretical models offer a compromise between theory and ease of use (Fortes & Okos, 1981). Semi-theoretical models are generally derived by simplifying general series solution of Fick's second law or modification of simplified models. But they are only valid within the temperature, relative humidity, air flow velocity and moisture content range for which they were developed. They require small time compared to theoretical thin layer models and do not need assumptions of geometry of a typical food, its mass diffusivity and conductivity (Parry, 1985). Among semi-theoretical thin layer drying models, the Henderson and Pabis model, the two-term model, the Lewis model, the Page model and the modified Page model are used widely (Table 1). The Henderson and Pabis model is first term of a general series solution of Fick's second law (Henderson & Pabis, 1961). The Henderson and Pabis model was used to model drying of corn (Henderson & Pabis, 1961), wheat (Watson & Bhargava, 1974), rough rice (Wang & Singh, 1978), peanut (Moss & Otten, 1989) and mushroom (Gürtaş, 1994). A poor fit during first 1 or 2 h of drying of corn was, however, reported due to the greater temperature difference between the kernel and air, and loss of accuracy due to the truncation of the series solution (Henderson & Pabis, 1961). Slope of the Henderson and Pabis model, coefficient k (see Table 1) is related to effective diffusivity when drying process takes place only in the falling rate period and liquid diffusion controls the process (Suarez, Viollaz & Chirife, 1980b; Madamba et al., 1996).

The two-term model is the first two terms of general series solution to Fick's second law, and has also been used to describe drying of agricultural products, regardless of particle geometry such as drying of corn (Henderson, 1974; Sharaf-Eldeen, Blaisdell & Hamdy, 1980), white beans and soybeans (Hutchinson & Otten, 1983), macadamia nut in-shell and kernel (Palipane & Driscoll, 1994). However, it requires constant product temperature and assumes constant diffusivity.

The Lewis model, where intercept is unity, is a special case of the Henderson and Pabis model. The Lewis model was used to describe drying of barley (Bruce, 1985), wheat (O'Callaghan, Menzies, & Bailey, 1971), shelled corn (Sabbah, Kenner & Meyer, 1972), cashew nuts, kernels (Chakraverty, 1984) and walnut (Anigbankpu, Rumsey & Thompson, 1980). The model, however, tends to overestimate the early stages and underestimate the later stages of the drying curve (Bruce, 1985).

The Page model is modification of the Lewis model to overcome its shortcomings (Page, 1949, cited in Bruce, 1985). The Page model has produced good fits in pre-

Table 1
Some semi-theoretical and empirical thin layer drying models used for mathematical of drying of grains, nuts and oilseeds

Model name	Equation	References
Fick's second law (in spherical coordinates)	$\partial M/\partial t = D[\partial^2 M/\partial r^2 + (2/r)(\partial M/\partial r)]$	Demirtaş et al. (1998)
The Henderson and Pabis model	$\mathrm{MR} = a\exp(-kt)$	Henderson and Pabis (1961)
The two-term model	$\mathrm{MR} = a\exp(-k_1 t) + b\exp(-k_2 t)$	Henderson (1974)
The Lewis model	$\mathrm{MR} = \exp(-kt)$	Bruce (1985)
The Page model	$\mathrm{MR} = \exp(-kt^n)$	Page (1949), cited in Bruce (1985)
The modified Page model	$\mathrm{MR} = \exp(-kt)^n$	Overhults et al. (1973)
The Thompson model	$t = a\ln\mathrm{MR} + b(\ln\mathrm{MR})^2$	Thompson et al. (1968)
The Wang and Singh model	$\mathrm{MR} = 1 + at + bt^2$	Wang and Singh (1978)

dicting drying of short grain and medium rough rice (Wang & Singh, 1978), soybean (White, Bridges, Loewer & Ross, 1981; Hutchinson & Otten, 1983), white bean (Hutchinson & Otten; 1983), shelled corn (Agrawal & Singh, 1977; Misra & Brooker, 1980), corn (Flood, Sabbah, Meeker & Peart, 1972), barley (Bruce, 1985), rapeseed (Pathak, Agrawal & Singh, 1991) and sunflower seeds (Syarief, Morey & Gustafson, 1984). The Page model was also modified by Overhults, White, Hamilton and Ross (1973) to describe drying of soybean.

Empirical models derive a direct relationship between average moisture content and drying time. They neglect fundamentals of the drying process and their parameters have no physical meaning. Therefore they cannot give a clear accurate view of the important processes occurring during drying although they may describe the drying curve for the conditions of the experiment (Keey, 1972; Irudayaraj, Haghighi & Stroshine, 1992). Among them, the Thompson model and the Wang and Singh model (see Table 1) have been found application in the literature. The Thompson model was used to describe shelled corn drying for temperatures between 60°C and 149°C (Thompson, Peart & Foster, 1968), and the Wang and Singh model was used to describe drying of rough rice (Wang & Singh, 1978).

Although roasting is an essential step of processing of nuts and oilseeds, there are limited literature about physical and biochemical changes taking place during roasting, namely drying, aroma formation, colour and texture development, lipid oxidation and nutritional losses. Since drying is probably the most important change during roasting, drying process during roasting of hazelnuts were characterised in the present study. To achieve that goal, the thin layer drying characteristics of hazelnut kernels during roasting operation were determined experimentally; a suitable thin layer drying model for describing the drying process was investigated; and effective diffusivity and activation energy of hazelnuts during roasting were calculated.

2. Material and methods

2.1. Preparation

Freshly harvested and sun-dried hazelnuts were supplied from Hazelnut Research Center (Giresun, Turkey) and stored in-shell at 4°C in vacuum plastic bags until experiments (at most two months). The samples were temperature equilibrated overnight and cracked using a modified laboratory scale grain miller to crack shells. After sizing the samples, 9–11 mm of hazelnut samples were used in the experiments. Initial moisture content of the hazelnuts was 5–6% wet basis.

2.2. Roasting system

The forced air pilot scale dryer-roaster (73 cm× 205 cm × 161 cm) (Pasilac, APV, UK) was used during experiments. The apparatus consisted of a heater, a centrifugal fan for generating an air stream, and a drying chamber (Fig. 1). The each nut sample was held in a rectangular (10 cm × 15 cm) wire mesh tray on the support (60 cm × 60 cm). Each tray could hold approximately 100 g of kernels. The size of the perforations (6 mm diameter) and the open area (>50%) were sufficiently large to reduce pressure drop due to perforations. Appropriate sliding gates of the dryer were opened so that air movement was downwards and uniformly distributed in the drying chamber using baffles.

As almost all the drying of grain and nut products occurs in the falling rate periods, during which drying rate is mainly controlled by internal diffusion of moisture, effect of air velocity on affect drying rate is insignificant above a critical air velocity value (Li & Morey, 1984; Treybal, 1984; Parry, 1985; Moss & Otten, 1989; Palipane & Driscoll, 1994; Shivhare, Raghavan & Bosisio, 1994; Madamba et al., 1996). Critical air velocity, below which drying rate is affected, was stated to be 0.102 m/s for grains (Henderson & Pabis, 1962) and 0.14 m/s for soybean and white beans (Hutchinson & Otten, 1983). Hence, air velocity was kept constant at 0.8 m/s throughout experiments so as not to affect drying rate by air velocity. Air velocity was measured (Testo, Model 400, UK) at the inlet of the drying chamber. Moreover, equilibrium moisture content was assumed to be 0 (Moss & Otten, 1989) since roasting temperatures (100–160°C) were higher or very close to the temperatures used in moisture content determination in which samples are dried at 104°C (Keme & Messerli, 1976; TSE, 1978).

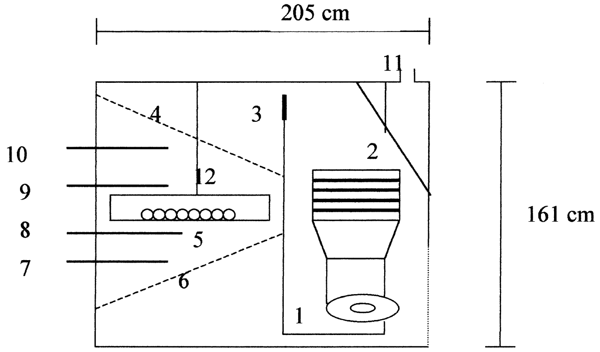

Fig. 1. Schematics of pilot plant roaster in vertical axis (not to scale) (Pasillac, APV, UK) and its instrumentation (1 – fan; 2 – heating element; 3 – baffle; 4,6 – perforated plate; 5 – sample tray; 7,10 – pressure drop; 8,9 – temperature sensors; 11 – air exhaust; 12 – point of velocity measurement).

2.3. Experimental procedure

Prior to placing the sample in the drying chamber, the equipment was run for at least 2 h to obtain steady-state conditions. The kernels as single layer were placed in the drying chamber in 12 small drying trays. Then, every 5 min for a period of 1 h, one tray was removed from the drying chamber in less than 10 s (Madamba et al., 1996), so that steady-state conditions were maintained during sampling. Roasting air temperatures were 100°C, 120°C, 140°C and 160°C. The roasted samples were cooled to room temperature in desiccators. Moisture content of each sample was determined in triplicates using 50 g of the samples by drying in a oven at 103°C for 4 h (TSE, 1978).

2.4. The statistical modelling procedure

Analysis of variance (ANOVA) was performed to find out effect of temperature on the drying of hazelnuts during roasting. The Henderson and Pabis model, the two-term model, the Lewis model, the Page model, the modified Page model, the Wang and Singh model and the Thompson model were fitted to the experimental drying data. Correlation coefficient and the mean square error (MSE) were used as criteria for adequacy of fit. The average of the relative percent difference between the experimental and predicted values or the mean relative deviation modulus (P) defined by Eq. (1) was used as a qualitative measure of the model adequacy (Lomauro, Bakshi & Labuza, 1985; Madamba et al., 1996; Palipane & Driscoll, 1994).

$$P = \frac{100}{n}\sum\frac{|M_i - M_{\mathrm{pri}}|}{M_i}, \tag{1}$$

where M_i is the moisture content at observation, M_{pri} the predicted moisture content at observation and n is the number of observations.

Initial selection of thin layer drying models was done using regression procedure. The drying coefficients or constants of the selected models were then related to the temperature to obtain functional relationships, using one-step regression technique.

The best model describing the thin layer drying characteristics of hazelnut kernels during roasting was chosen as the one with the highest correlation coefficient and the least error sum of squares and the least mean relative deviation modulus (Lomauro et al., 1985; Madamba et al., 1996; Palipane & Driscoll, 1994).

3. Results and discussion

One-way ANOVA indicated that temperature significantly affects the drying during roasting of hazelnuts ($p < 0.0001$). Fig. 2 shows the effect of increasing roasting air temperature on the drying of hazelnuts during roasting. A higher roasting temperature resulted in a higher drying rate. During first 25 min of roasting, 44.1%, 50.6%, 73.4%, 90.1% of the moisture were removed at roasting air temperatures of 100°C, 120°C, 140°C, 160°C, respectively. Similar higher initial dying rates were reported by Madamba et al. (1996) during garlic drying and by Palipane and Driscoll (1994) during macadamia drying. Moreover, many researchers reported drying air temperature to be the single and the most important factor affecting drying rate. They pointed out that use of higher drying air temperature increases drying rate significantly. These included Puiggali, Bastale and Ndue (1987) and Demirtaş et al. (1998) for hazelnuts, Karataş and Battalbey (1991) for pistachio kernel, Chinnan (1984) for in-shell pecans, Syarief et al. (1984) for sunflower seeds, Ece and Cihan (1993) for rough rice, Lebert and Bimbenet (1991) for plum drying.

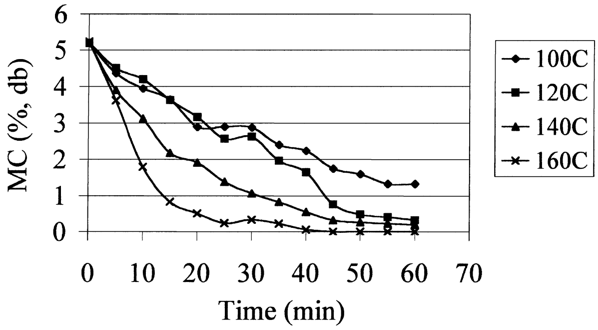

Fig. 2. Effect of temperature on the moisture content of the hazelnuts during roasting.

As expected the drying process took place in the falling rate period as the moisture content (around 6% db) was already very low at the beginning of the roasting. Almost all the drying of grain and nut products occur in the falling rate periods during drying/roasting (Husain, Chen, Clayton & Whitney, 1972; Suarez et al., 1980a,b; Chinnan, 1984; Syarief et al., 1984; Parry, 1985; Shepherd & Bhardwaj, 1988; Moss & Otten, 1989; Karataş & Battalbey, 1991; Lebert & Bimbenet, 1991; Pathak et al., 1991; Crisp & Woods, 1994; Palipane & Driscoll, 1994; Shivhare et al., 1994; Demirtaş et al., 1998).

At such high roasting temperatures, non-enzymatic browning reaction is favoured which occurs between carbonyl group of a reducing sugar with free, uncharged amine group of amino acid or protein with the loss of one mole of water. The reaction was related to formation of colour and aroma (Ames, 1988; Troller, 1989; Labuza & Braisier, 1992; Jinap et al., 1998). Since aroma compounds are volatiles and lost during roasting, some of the dry matter loss can be attributed to non-enzymatic browning reaction, especially at higher roasting air temperatures. Further research is however, necessary to find out effect of non-enzymatic browning reaction on dry matter loss during roasting.

3.1. Calculation of effective diffusivity and activation energy

Since the drying during roasting of hazelnuts occurs in the falling rate period only and liquid diffusion controls the process, Fick's second law can be used to describe drying process during roasting hazelnuts. General series solution of Fick's second law in spherical coordinates is given below (Eq. (2)) in which constant diffusivity and spherical hazelnut with a diameter of 0.01 m was assumed:

$$\frac{\overline{M} - M_e}{M_i - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 D \pi^2}{R^2} t \right), \tag{2}$$

where D is the effective diffusivity (m^2/s) and R is the radius of the hazelnut (m). First term of Eq. (2) is known as the Henderson and Pabis model (see Table 1). The slope, coefficient k, of the Henderson and Pabis model is related to the effective diffusivity:

$$k = \frac{D\pi^2}{R^2}. \tag{3}$$

The Henderson and Pabis model obtained r^2 greater than 0.92 in experimental moisture ratio prediction (see Table 2). Similar findings were reported by Moss and Otten (1989) for peanut roasting, by Watson and Bhargava (1974) for wheat drying and by Suarez et al. (1980b) for grain sorghum drying. Average of intercept value, constant a, of the Henderson and Pabis model was 1.131 over the experimental conditions used in this study. But theoretical intercept value, estimated with first term of Eq. (2), has a value of ln $(6/\pi^2)$ and is equal to -0.498. This deviation can be attributed to the short roasting time employed in the study since the Herderson and Pabis model is generally recommended for long drying times (Madamba et al., 1996).

Table 2
Curve fitting criteria for the thin layer drying models for the roasting of hazelnuts

Model	T (°C)	r^2	MSE[a]	P (%)[b]
The Henderson and Pabis model	100	0.98	0.0045	4.95
	120	0.92	0.0849	23.34
	140	0.99	0.0130	8.62
	160	0.95	0.2922	41.39
The Lewis model	100	0.979	0.0043	5.00
	120	0.882	0.1112	27.15
	140	0.990	0.0127	8.27
	160	0.950	0.2708	40.66
The Page model	100	0.973	0.0125	33.67
	120	0.949	0.0537	186.19
	140	0.993	0.0044	11.75
	160	0.969	0.0252	217.24
The modified Page model	100	0.973	0.0125	6.57
	120	0.949	0.0537	24.06
	140	0.993	0.0044	8.47
	160	0.969	0.0252	44.44
The two-term model	100	0.99	4.978	0.0122
	120	0.974	40.18	0.0631
	140	0.999	10.13	0.0032
	160	0.995	59.821	0.0129
The Wang and Singh model	100	0.975	0.0015	4.82
	120	0.986	0.0015	15.27
	140	0.982	0.0018	19.87
	160	0.879	0.0129	1363.05
The Thompson model	100	0.983	7.07	9.55
	120	0.972	11.62	8.66
	140	0.987	5.26	5.41
	160	0.959	17.00	11.73
The Thompson model	All[c]	0.954	17.29	14.43

[a] Mean square error.

[b] Mean relative deviation modulus (P).

[c] Results of one-step regression.

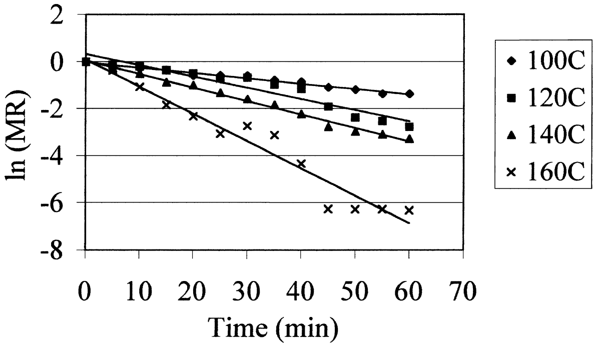

Fig. 3. Experimental and predicted ln(MR) vs time.

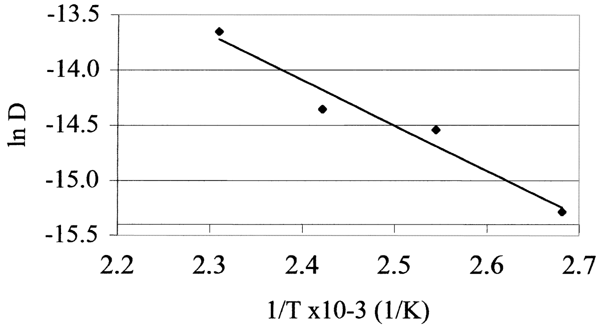

Fig. 4. Arrhenius-type relationship between effective diffusivity and temperature.

Effective diffusivity was calculated by Eq. (3), using slopes derived from the linear regression of ln (MR) vs time data shown in Fig. 3. Generally, an effective diffusivity is used due to limited information on the mechanism of moisture movement during drying and complexity of the process (Madamba et al., 1996). The effective diffusivities (D_{eff}) during roasting of hazelnuts varied from 2.301×10^{-7} to 11.759×10^{-7} m^2/s over the temperature range 100–160°C. Similar variations were also observed during drying of garlic (Madamba et al., 1996) and pistachio nuts (Karakaş & Battalbey, 1991). Effective diffusivities found in this study are higher than the reported diffusivities for food materials during drying which is 10^{-9} and 10^{-11} m^2/s (Madamba et al., 1996). The higher diffusivities can be attributed to the higher temperatures employed in the study. Rizvi (1986) stated that effective diffusivities depend on drying air temperature besides variety and composition of the material. Isosteric heat of sorption which is a measure of moisture mobility within the food is another factor that affects effective diffusivity (Madamba et al., 1996).

Effect of temperature on effective diffusivity is generally described using Arrhenius-type relationship to obtain better agreement of the predicted curve with experimental data (Henderson, 1974; Mazza & Le Maguer, 1980; Suarez et al., 1980a; Steffe & Singh, 1982; Pinaga, Carbonell, Pena & Miguel, 1984; Carbonell, Pinaga, Yusa & Pena, 1986; Crisp & Woods, 1994, Gürtaş, 1994; Madamba et al., 1996). Crisp and Woods (1994) reasoned that temperature is not a function of radial position in the grain under normally experienced drying conditions, and diffusivity varies more with temperature than moisture content:

$$D = D_{\mathrm{o}} \exp\left(-\frac{E_{\mathrm{a}}}{RT_{\mathrm{a}}}\right), \tag{4}$$

where D_{o} is a diffusivity constant equivalent to the diffusivity at infinitely high temperature and E_{a} is the activation energy (kJ/kg). A plot of ln D vs reciprocal of the absolute temperature (T_{a}) gives the energy of activation as a slope and constant D_{o} as the intercept (Fig. 4). Then, Arrhenius-type temperature dependence of effective diffusivity can be expressed as

$$D = 0.014 \exp\left(-\frac{4099.8}{T_{\mathrm{a}}}\right) \tag{5}$$

from which the activation energy for water diffusion can be found to be 1891.6 kJ/kg. It is higher than activation energies of onion drying (1200 kJ/kg) (Mazza & Le Maquer, 1980), garlic slices drying (989 kJ/kg) (Madamba et al., 1996), rice drying (1183 kJ/kg) (Pinaga et al., 1984), mushroom drying (1680 kJ/kg) (Gürtaş, 1994) and pistachio nut drying during the first falling rate period (1252.6 kJ/kg) (Karataş & Battalbey, 1991) but lower than activation energy of paprika drying (2036 kJ/kg) (Carbonell et al., 1986) and pistachio nut drying during the second falling rate period (2412.5 kJ/kg) (Karataş & Battalbey, 1991).

3.2. *Modelling of the thin layer drying characteristics of hazelnut roasting*

Thin layer drying models, the Henderson and Pabis model, the two-term model, the Lewis model, the Page model, the modified Page model, the Wang and Singh model and the Thompson model were used to describe the drying process during roasting of hazelnuts. The models were evaluated based on MSE, correlation coefficient (r^2), and the mean relative deviation (P) modulus (Lomauro et al., 1985; Madamba et al., 1996; Palipane & Driscoll, 1994). These curve fitting criteria for the seven models were shown in Table 2.

The Henderson and Pabis, the two-term, the Page, the modified Page and the Thompson models obtained r^2 greater than acceptable r^2 value of 0.90 (Madamba et al., 1996) at all roasting air temperatures. However, the Lewis model at 120°C roasting air temperature and the Wang and Singh model at 160°C roasting air temperature produced r^2 value lower than 0.9. Among the thin layer drying models, the two-term model obtained the highest r^2 values in the temperature range of the study. The Thompson model produced the highest MSE which was in the range 7–17. The Wang and Singh model produced the lowest MSE. The percent mean relative deviation modulus (P), indicating deviation of the experimental data from the predicted line, is in the range of 4.95 and 59.82 in the semi-theoretical models except for the Page model. A higher variability between 11.75 and 217.24 was observed in terms of P for the Page model. Empirical models produced lower P values expect for the Wang and Singh model at 160°C. At that temperature, the Wang and Singh model predicted MR lower than zero which caused to increase P considerably after 30 min. The range of P for the Wang and Singh model and for the Thompson model was 4.82–1363.1 and 5.41–11.73, respectively. Semi-theoretical models were rejected in spite of their high r^2 due to their high P values because a P value lower than 10% is recommended for the selection of models and r^2 was stated not to be a good criteria for evaluating non-linear mathematical models (Lomauro et al., 1985; Chen & Morey, 1989; Madamba et al., 1996). Moreover, the Wang and Singh model were rejected due to its high P value at roasting air temperature of 160°C despite its low MSE and high r^2 at other temperatures. The Thompson model was selected due to its lower P value and comparable r^2 values to fit the experimental data on roasting of hazelnuts. The model coefficients were calculated using Levenberg–Marquard estimation method. The drying coefficients a and b were then related to the roasting air temperature to obtain functional relationships, using one-step regression procedure as recommended by Madamba et al. (1996). Drying coefficients of Thompson model were related to roasting air temperature using first degree polynomial:

$$a \text{ or } b = C_0 + C_1 T, \tag{6}$$

where C_0 and C_1 are model coefficients. The linear temperature dependence of drying constants was also used by Madamba et al. (1996) for garlic drying, Hutchinson and Otten (1983) and Overhults et al. (1973) for soybean drying, Syarief et al., (1984) for sunflower seed drying (Bruce, 1985) for barley drying.

The results of the one-step regression procedure together with curve fitting criteria of r^2, MSE and P-value were shown in Table 2. The Thompson model described thin layer roasting of hazelnuts with drying constant as a linear function of temperature with acceptable MSE and P-value, and high r^2. The model with its coefficients is

$$t = (-116.05 + 0.656T)\ln \mathrm{MR} + (-19.89 + 0.122T)(\ln \mathrm{MR})^2 \tag{7}$$

Fig. 5 shows the Thompson model curve for the experimental data of thin layer roasting of hazelnuts for the temperature range of 100–160°C. Fig. 6 shows comparison of actual and predicted values for Eq. (7). The experimental data generally banded around 45°C straight line which shows the suitability of Eq. (7) in describing behaviour of hazelnuts during roasting.

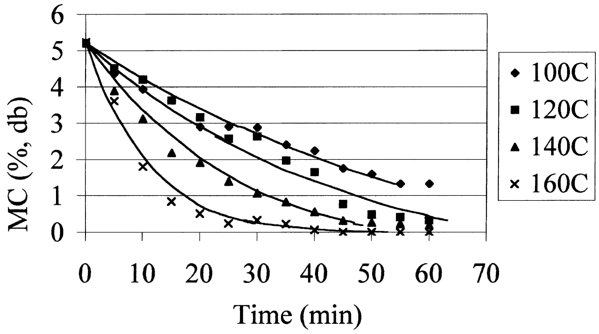

Fig. 5. The Thomson model fitted to drying during hazelnut roasting.

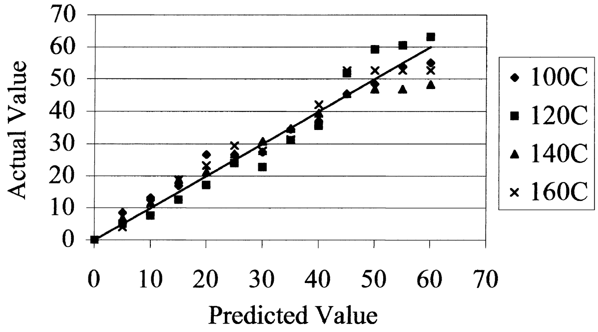

Fig. 6. Comparison of actual and predicted value by the Thompson model.

4. Conclusions

Roasting is one of the most important steps of the nut processing. Drying is one of the important changes occurring during roasting of nuts. In this study, drying during thin layer roasting of hazelnuts was characterised. Hazelnut drying during roasting occurred in the falling rate period. Temperature dependence of the diffusivity coefficients was described by Arrhenius-type relationship. The activation energy for moisture diffusion was found to be 1891.6 kJ/kg. Thin layer drying characteristics of hazelnut roasting were satisfactorily described by empirical Thompson model with the linear temperature dependence. Further research about effect of initial moisture content, air velocity, air relative humidity and layer thickness on drying characteristics and quality of hazelnuts is necessary for optimisation of hazelnut roasting and development of hazelnut roasters.

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