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Kinetic Modeling of Mass Transfer During Roasting of Soybeans Using Combined Infrared-Hot Air Heating

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ABSTRACT: Roasting is one of the widespread methods for processing of nuts and beans that significantly enhances the flavor, color, texture and appearance of the products. In this research the kinetics and modeling of soybean roasting using combined infrared-hot air system and consumption of energy were investigated. The effect of the hot air temperature (160, 180 and 200 °C), infrared powers (200, 250 and 300 W) and combined hot air temperature and IR powers (120, 140 and 160 °C- 130, 165 and 200 W) on roasting rate of soybeans were evaluated. The results showed that the effect of hot air temperature, infrared power and combined hot air temperature and IR power on the roasting rate of soybean were statistically significant and the roasting process occurred within the falling rate period. Among the five thin-layer roasting models fitted to the experimental data, the page model was the best to describe the roasting behavior. Fick's law of diffusion was used to determine the effective moisture diffusivity, which varied between 1.727×10^{-9} to 4.518×10^{-9} m^2/s. Activation energy was estimated by Arrhenius and modified Arrhenius equations as 22.0234 kJ/mol and 4.3778 kW/kg, respectively. Comparison of roasting methods showed that minimum energy was consumed in the infrared method (0.0905 kWh) and maximum energy was recorded for hot air roasting (1.752 kWh), thus infrared radiation could be considered as a promising technique for roasting of soybeans due to lower energy cost.

Keywords: *Hot Air Temperature, Infrared Power, Roasting, Soybeans.*

Introduction

Soybean is recognized as a healthy food because it is a good source of essential nutrients including proteins, oil and several bioactive compounds (Dondee *et al.*, 2011) and is receiving increased attention due to its low cost and high nutritive value (Kato *et al.*, 1980). Although soybean has been used for human consumption in some countries in Asia, there is a limitation to its use in other parts of the world. The most significant factor responsible for such limitation is probably the characteristic flavor of soybean. Raw soybean has beany, bitter and astringent flavors. Therefore to improve its consumption, the particular flavor of raw soybean must be removed. Roasting is one of the methods for this purpose.

Roasting creates a desirable flavor without any beany odor or bitter taste (kato *et al.*, 1980) and significantly enhances the flavor, color, texture and appearance of the beans and nuts (Ozdemir & Devres, 1999). The roasted product is delicate, uniquely nutty and widely enjoyed as compared to raw bean. Roasting also removes bitter taste of soybean, inactivates the enzymes and destroys undesirable microorganisms and

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food contaminants (Kato *et al.*, 1980); therefore roasted soybean has the potential to be used as snacks. Hot air roasting is a common practice to which nuts and beans are subjected to before being used as a snack or before being incorporated into food (Nebesny *et al.*, 1998). Since hot air roasting is one of the most energy-intensive processes, new roasting techniques and roasters must be designed and studied to minimize the energy cost in the roasting process (Kocabiyik & Tezer, 2009).

Infrared roasting has gained attention as an alternative roasting method for beans and nuts. The use of infrared roasting has several advantages in comparison with the traditional convective roasting methods. Heat efficiency, high diffusion coefficient, low roasting time and compact equipment are advantages of this novel method (Wu *et al.*, 2014).

Yang *et al.* (2010) developed two new roasting methods for almonds; infrared roasting and sequential infrared and hot air roasting (SIRHA). Compared with the traditional hot air roasting, SIRHA heating can produce roasted almonds with up to 30–70% reduction in processing time and meet pasteurization requirements for producing medium degree roasted almonds at 130, 140, and 150°C.

Combined infrared and hot air method has been widely applied for drying of various foodstuffs including carrots, potatoes (Hebber *et al.*, 2004), pineapple rings (Ponkham *et al.*, 2012) and onion slices (Kumar *et al.*, 2006). The combined technique was found to accelerate heat and mass transfer, leading to a shorter processing time and lower energy consumption (bagheri *et al.*, 2016) compared to hot air method.

Roasting rate of nuts depends on the heat and mass transfer characteristics of the product being roasted. Knowledge of temperature and moisture distribution in the product is vital for equipment and process design, quality control, choice of appropriate storage and handling practices.

Mathematical models that describe roasting mechanisms of foods can provide the required temperature and moisture information (Parti, 1993). The prediction of the soybeans roasting rate at various roasting conditions is important for designing roasting process and systems. Because most of the roasting process involves simultaneous and often coupled multiphase heat, mass and momentum transfer phenomena (Yilbas *et al.,* 2003), the roasting process is one of the most complex and least understood process.

The thin-layer equations are useful tools for mathematical models of roasting. The thin-layer models developed from the known roasting rate curves are practically applied in the food system, and thorough reviews on thin-layer models have been published (Erbay & Icier, 2009). Among mathematical models, thin layer models have been found wide application due to their ease of use and lack of required data in complex theoretical models (Madamba *et al.*, 1996). Thin-layer models have been studied in the drying and roasting of fruits, meat and other natural products with many different roasting or drying methods (Ozdemir & Devres, 1999).

Although roasting is an essential step of processing of beans, oilseeds and nuts, there are limited literature about new methods for roasting process. No work has been reported for roasting of soybean using sequential or combined infrared and hot air. Therefore in the present study, the thin layer roasting characteristics of soybean during infrared-hot air roasting operation were determined experimentally; a suitable thin layer roasting model was fitted for describing the roasting process; and effective diffusivity and activation energy of soybean were also calculated during roasting.

Materials and Methods

- Samples

Freshly harvested and sun-dried soybean (Gorgan 3 variety) was obtained from the Agricultural Research Institute of Gorgan (Golestan, Iran) and stored at 4°C in vacuum plastic bags until required. Soybean samples with the same dimensions (thickness, width, length) were used in the experiments. Initial moisture content of the soybean was 6.2% (d.b.) and the three principal dimensions, namely thickness, width and length, were 6.03, 7.35 and 8.46 mm, respectively.

- Sample preparation

The raw soybeans were washed and soaked in 25% (w/v) salt solution for 10 hours. After tempering, the moisture content of soaked soybeans samples were increased to 104% (d.b.) and the three principal dimensions, namely thickness, width and length, were 6.88, 8.66 and 10.46 mm, respectively. The soaked samples were strained off and used for roasting process.

- Roasting System

The hot air-infrared radiation roaster was used during experiments. The apparatus consisted of heating elements (4 electrical elements with power 750 watts), scale, pilot unit, a centrifugal fan, infrared radiator and a roasting chamber.

- Roasting experiments

Prior to placing the sample in the roasting chamber, the equipment was run for at least 2h to obtain a steady-state condition. Soybeans were spread as a thin-layer on the roasting trays and placed in the roasting chamber and the test started and the weight of the sample was continuously monitored and recorded every 10S during roasting process. After each roasting experiment, the sample was oven-dried at 105 ± 2°C to determine the moisture content (Kashaninejad *et al.*, 2003).

- Roasting rate

Roasting rate (kg water/kg dry solid × second) of soybean during roasting process was calculated using Eq. (1):

$$Roasting\ rate = \frac{MC_{t+dt} - MC_t}{dt} \quad (1)$$

Where, MC_{t+dt} is the moisture content of the sample at any time (kg water/kg dry matter), MC_t is its initial moisture content (kg water/kg dry matter) and d*t* is the roasting time (second) (Kar & Gupta, 2003).

- Energy consumption

The energy consumption in each period of roasting was measured using Power Analyzer (Lutron, model, DW-6090 A, Taiwan). Measurement of current and power can be carried out directly with test cables that come with the device or indirectly using the clamps. The device has an RS-232 interface, and software to analyze the results and transfer the data to a computer. Finally energy consumption in the roaster was calculated using Eq. (2).

$$\text{Energy} = \int_{t=1}^{t=1500} Pt \quad (2)$$

- Mathematical modeling and analysis of roasting data

The effect of different roasting parameters (hot air temperature and infrared power) on roasting behavior of soybeans was determined using two factors in a completely randomized design (CRD) following the analysis of variance (ANOVA) method. Each reported value is the mean of three determinations and statistical analysis was performed (Minitab, version 16) with a significance level of $P<0.05$. Significant differences between treatment means were compared using Duncan's multiple range tests.

Five well-known models of thin-layer roasting were applied to find out the suitable model for the roasting process of soybeans. The moisture ratio (MR) was defined by Eq (3):

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (3)$$

Where, M, M_0 and M_e are the moisture content of the samples at any roasting time, initial moisture content and the equilibrium moisture content, respectively. Since the M_e was very small, the moisture ratio equation was simplified to M/M_0 (Akgun & Doymaz, 2005). The roasting data were fitted to models and their parameters were determined by the sigma plot software (Systat Software, Inc., Sigma Plot 12) according to the nonlinear modeling procedure. The performance of a model was 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 Sum Square Error (SSE) (Eqs. 4 and 5, respectively). A model with the maximum of R^2 and the minimum of SEE shows the best performance (Kingsly & Singh, 2007):

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,avg}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{exp,avg}\right)^2} \quad (4)$$

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

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, MR_{exp} and MR_{pre} are the average of sum of the $MR_{exp.i}$ and $MR_{pre,i}$, respectively.

Results and Discussion

- Roasting kinetics

The effects of hot air temperature, infrared power and combination of infrared power and hot air temperature on moisture content changes of soybeans during roasting as a function of time are presented in Figure 1. During 25 min of roasting, 97%, 98.9% and 100% of the moisture were removed from soybeans at roasting air temperatures of 160°C, 180°C and 200°C, respectively. It can be observed that the moisture decreased faster at higher roasting temperatures in all the cases. The moisture content of soybeans reduced exponentially as the roasting time increased. Continuous decrease in moisture content indicates that diffusion governed the internal mass transfer (Haghi & Amanifard, 2008). In addition, higher roasting air temperature decreased the moisture content faster. The similar results were reported for roasting of hazelnuts (Ozdemir & Devres, 1999), drying of green and red peppers (Kaymak-Ertekin, 2002) and pumpkin (Doymaz, 2007).

An increase in IR power significantly increased the moisture removal rate. As expected at higher IR power the higher heat absorption resulted in higher product temperature, higher mass transfer driving force and consequently faster roasting rate (Afzal *et al.*, 1999).

Nomenclature			
d.b	Dry base	M	Moisture
h	Hour	D_{eff}	effective moisture diffusivity
MC	Moisture content	N	number of experimental data points
MR	Moisture ratio	m	Sample mass
R	Gas constant	D_0	The pre-exponential factor of Arrhenius equation
t	Time	E_a	Activation energy
P	Infrared power	T	Temperature

Figure 1 shows the effect of combination of IR power and hot air on moisture content of soybeans during roasting. This Figure reveals that the roasting process is characterized by a progressive decrease in moisture content with time depending on the infrared power and temperature of hot air. The synergistic effect of infrared and hot-air led to significant increasing of moisture removal and consequently faster roasting rate.

- *Roasting rate*

The roasting rate of soybeans using hot air and infrared are shown in Figure 2. It is found that there was no constant rate period in the roasting process of soybeans and all process occurred in the falling rate period. This indicates that diffusion is the controlling physical mechanism regulating the moisture transfer in roasting of soybeans.

The increase in the hot air temperature increased the roasting rate rapidly and also roasting rate decreased with decreasing moisture content. Therefore, higher roasting temperature resulted in a higher roasting rate. Similar findings were reported by Palipane and Driscoll (1994) during macadamia drying and by Madamba *et al.* (1996) during garlic drying. The high rate in roasting process with increased temperature may be due to the increase in water vapor pressure that the soybeans, that increased the migration of moisture, especially when the roasting occurs only in falling rate period.

The effect of infrared power on the roasting rate of the soybeans during roasting is shown in Figure 2. It shows roasting rate increased with infrared power. This can be explained by the rapid heating of the product, thus accelerating moisture migration toward the surface of the product

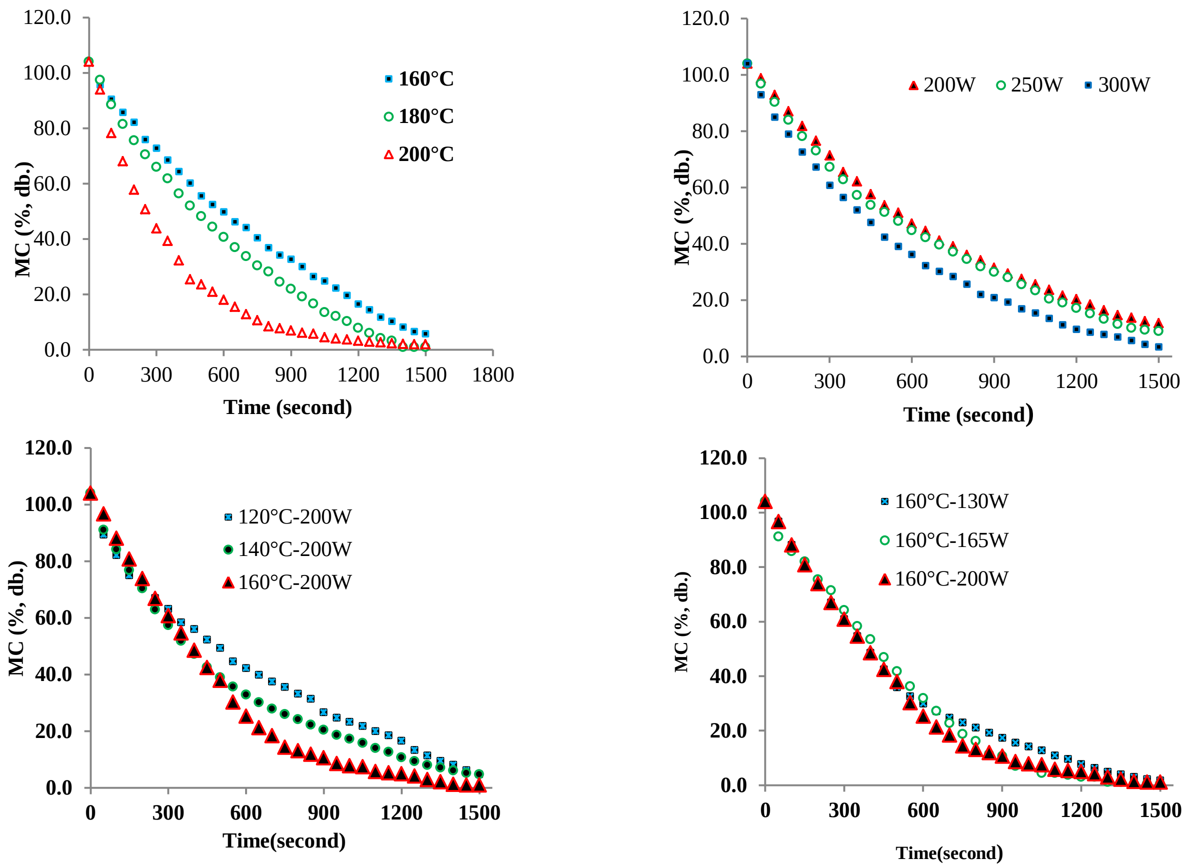

Fig. 1. The effect of different conditions on the moisture content of soybeans during roasting

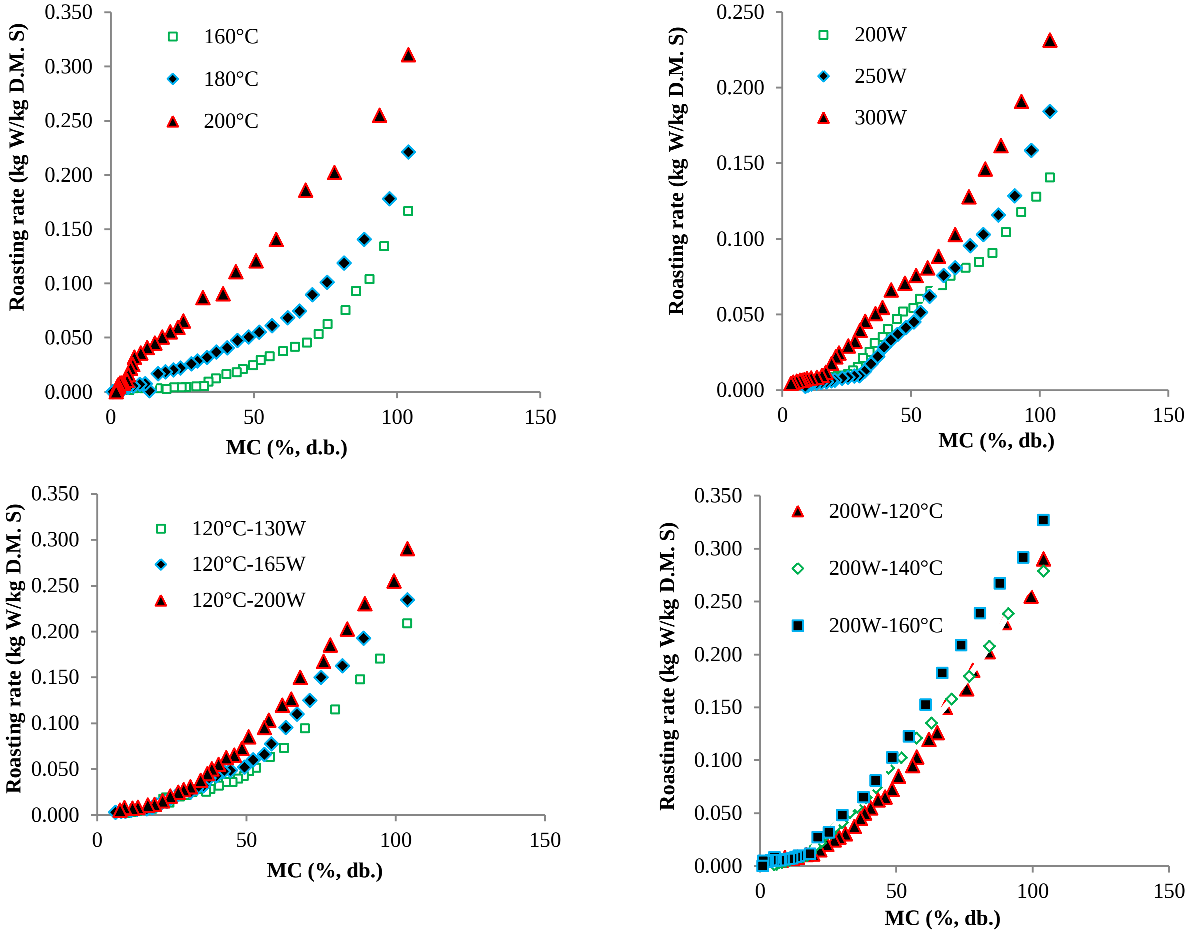

Fig. 2. The influence of different conditions on the roasting rate of soybeans during roasting

where it's carried away. The increase in infrared power caused a rapid increase in the temperature at the surface of soybeans, resulting in an increase of the water vapor pressure inside the soybeans (Datta & Ni, 2002) and thus in higher roasting rate.

It is clear that roasting rate is higher under combined infrared-hot air roasting than in infrared and hot air alone. The use of combined infrared-hot air provides necessary heat of vaporization from deep inside the kernel and slightly hot air to carry away the evaporated moisture. Therefore, the increase of roasting rate is observed with the increase temperature and infrared power. This means that at high temperature and infrared power, the heat and mass transfer is higher and the water loss is excessive. During the roasting process, the roasting rate was higher in the beginning of the process and thereafter decreased with a decrease of moisture content in the soybeans. The results were consistent with the observations made by different authors on drying of various agricultural products (Ponkham *et al.*, 2012).

- *Mathematical modeling*

The moisture ratio-roasting time values at each roasting condition were fitted to five models by applying the nonlinear regression analysis technique. The best model for each treatment was obtained using comparison of statistical parameters of R^2 and SSE. The results of the statistical computing are shown in Table 1. The R^2 values for all models were above 0.95.

Among the thin-layer roasting models, the Page model represented the roasting kinetics of soybeans with higher R^2 values and lower SSE values for all roasting conditions (Table 1). It is clear that the R^2 and SSE values of this model were varied between 0.991 and 0.999, 0.004 and 0.027, respectively.

In order to validate the selected model, plot of experimental and predicted MR by Page model is shown in Figure 3 for some roasting conditions. A good agreement was observed between experimental and predicted MR obtained from page model at each roasting conditions for soybeans, which banded around the straight line (X=Y). It proved the feasibility of the selected model in describing the roasting behavior of soybeans. Ozdemir and Devres (1999) reported that Thompson model was the best mathematical model for describing the roasting behavior of the hazelnuts.

Table 1. The statistical results obtained from the selected models for roasting of soybeans

Process codes	selected models									
	Newton		Page		Logarithmic		Two-term		Midilli	
	R^2	SSE	R^2	SSE	R^2	SSE	R^2	SSE	R^2	SSE
IR200	0.971	0.056	0.996	0.018	0.999	0.005	0.989	0.014	0.985	0.025
IR250	0.984	0.096	0.994	0.012	0.986	0.023	0.989	0.013	0.971	0.038
IR300	0.963	0.060	0.998	0.027	0.996	0.031	0.986	0.020	0.982	0.076
HA160	0.986	0.089	0.994	0.004	0.998	0.004	0.979	0.015	0.968	0.045
HA180	0.965	0.056	0.998	0.018	0.995	0.006	0.981	0.008	0.967	0.057
HA200	0.974	0.068	0.999	0.008	0.994	0.009	0.993	0.015	0.985	0.036
IR130-HA120	0.982	0.078	0.988	0.017	0.995	0.020	0.987	0.016	0.981	0.067
IR165-HA140	0.975	0.076	0.996	0.015	0.997	0.027	0.988	0.024	0.984	0.086
IR200-HA160	0.952	0.52	0.993	0.007	0.998	0.017	0.985	0.009	0.976	0.075
IR130-HA140	0.942	0.012	0.997	0.006	0.989	0.007	0.986	0.015	0.979	0.045
IR165-HA120	0.964	0.081	0.989	0.015	0.992	0.015	0.988	0.019	0.989	0.092
IR200-HA120	0.958	0.038	0.991	0.016	0.995	0.020	0.987	0.027	0.990	0.046
IR130-HA160	0.957	0.039	0.993	0.005	0.997	0.008	0.986	0.030	0.978	0.015
IR165-HA160	0.948	0.057	0.995	0.005	0.994	0.011	0.980	0.022	0.969	0.086
IR200-HA140	0.946	0.048	0.997	0.009	0.998	0.018	0.989	0.009	0.986	0.046

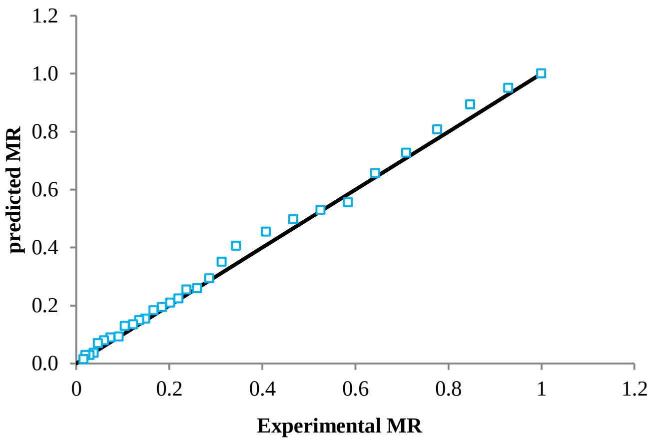

Fig. 3. Comparison of actual and predicted MR values by the Page model for roasting of soybeans (160°C-200W).

- *Effective moisture diffusivity*

Since the roasting of soybeans occurs in the falling rate period and liquid diffusion controls the process, Fick second law can be used to describe the roasting process of soybeans.

Crank (1975) solved this equation and introduced the following equations (6 and 7) which can be used for slab geometry with uniform initial moisture diffusion, constant diffusivity and insignificant shrinkage: where, D_{eff} is the effective diffusivity (m^2/s) and L is the half thickness of the slab in samples (m).

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{-(2n+1)^2\pi^2 D_{eff}t}{4l^2}\right] \quad (6)$$

$$MR = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2 D_{eff}t}{4l^2}\right] \quad (7)$$

As it is obvious, D_{eff} can be calculated from the slope of Eq. (7) using natural logarithm plot of MR versus roasting time.

The effective moisture diffusivity of a foodstuff characterizes its intrinsic mass transport properties of moisture including molecular diffusion, liquid diffusion, vapor diffusion, hydrodynamic flow and other possible mass transport mechanisms (Karathanos *et al.*, 1990). The effective moisture diffusivity (D_{eff}) during roasting of soybeans using hot air varied from 2.0744×10^{-9} to 3.4572×10^{-9} m^2/s in the temperature range of 160-200^{0}C (Table 2). It is clear that the D_{eff} value increased greatly with increasing temperature of hot air. Rizvi (2005) stated that effective diffusivity depends on hot air temperature besides variety and composition of the material.

The effective moisture diffusivity (D_{eff}) values for different infrared powers are given in Table 2 and ranged from 1.7266×10^{-9} to 2.2989×10^{-9} m^2/s. The D_{eff} values increased greatly with increasing infrared power. This might be explained that the increase in infrared power, causing a rapid rise in the temperature of the soybeans, which increased the vapor pressure. This led to faster roasting rate and increasing the effective moisture diffusivity. Roasting at 200 W had the highest value of effective moisture diffusivity and the lowest value was obtained for 130 W.

Table 2. The effective moisture diffusivity and energy consumption during roasting of soybeans

	Infrared power (W)	Temperature hot air (^{0}C)	Process codes	$D_{eff}\times10^{-9}$	EC (kWh)
Infrared system	200		IR200	1.727^c	0.0906^c
	250		IR250	1.834^b	0.1070^b
	300		IR300	2.299^a	0.1287^a
Hot air system		160	HA160	2.074^b	1.112^c
		180	HA180	3.343^a	1.425^b
		200	HA200	3.457^a	1.752^a
Combined HA- IR	130	120	IR130-HA120	1.766^f	0.724^d
	165	140	IR165-HA140	1.998^e	0.807^c
	200	160	IR200-HA160	2.098^e	0.889^{ab}
	130	140	IR130-HA140	2.210^d	0.856^b
	165	120	IR165-HA120	2.339^d	0.605^e
	200	120	IR200-HA120	2.629^c	0.552^f
	130	160	IR130-HA160	3.722^c	0.924^a
	165	160	IR165-HA160	4.206^b	0.901^a
	200	140	IR200-HA140	4.518^a	0.789^c

Table 2 shows the effect of combined infrared-hot air on the effective moisture diffusivity of soybeans. It is clear that effective moisture diffusivity is higher under combined infrared-hot air roasting than infrared or hot air alone. The effective moisture diffusivity increased from $1.76\times10^{-11} m^2/s$ to $4.51\times10^{-11} m^2/s$ for soybeans roasted with combined infrared-hot air. This increase might be due to higher heat in combined infrared-hot air process than the infrared and hot air process alone.

While limited reports are available for effective moisture diffusivity of roasting process, 10^{-9} to $\times10^{-11} m^2/s$ have been reported for drying of various food materials (Babalis & Belessiotis, 2004). Ozdemir and Devres (1999) stated that effective diffusivity during roasting of hazelnuts varied from 2.301×10^{-7} to $11.759\times10^{-9} m^2/s$ on the temperature range of 100-160^{0}C.

- *Activation energy*

In hot air roasting, activation energy was calculated using the Arrhenius equation (Singh & Gupta, 2007) which is presented as:

$$D_{eff} = D_o \exp\left[-\frac{E_a}{R(T)}\right] \tag{8}$$

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 roasting temperature (K) and R is the gas constant (kJ/(mol.K)). The E_a can be calculated from the slope of the plot ln (D_{eff}) versus 1/T.

Temperature is not a directly measurable parameter in the infrared power during roasting process in this study. Therefore the calculation of activation energy, modified form of Arrhenius equation (Eq.9) derived by Dadali and Ozbek (2008) was used that shows the relationship between the effective diffusivity and the infrared power to sample mass

$$D_{eff} = D_o \exp\left[-\frac{E_a m}{p}\right] \tag{9}$$

Where D_0 is the pre-exponential factor of Arrhenius equation (m^2/s), E_a is the activation energy (W/kg), P is the infrared power (W) and m is the sample mass (kg). In this situation E_a can be calculated from the slope of the plot ln (D_{eff}) versus m/P.

Temperature dependence of the diffusivity coefficients was described by an Arrhenius-type relationship. The E_a can be calculated from the slope of the plot on ln(D_{eff}) vs. 1/(T+273.15) (Figure 4).

Finally, the estimated values of D_0 and E_a for moisture diffusion were determined from the Arrhenius type exponential equation (Eq. 10) as $1.005\times10^{-6} m^2/s$ and 22.0234kJ/mol, 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) and hazelnuts roasting (1891.6 kJ/kg) (Ozdemir & Devres, 1999). Baik and Marcotte (2002) reported a similar behavior; that is an exponential increase in the moisture

$$D_{eff} = 1.005 \times 10^{-6} \exp\left[-\frac{22.0234}{R(T+273.15)}\right] \tag{10}$$

The activation energy for roasting process with infrared power was calculated from the slope of the plot on ln(D_{eff}) versus m/p. The results show a linear relationship due to modified Arrhenius type exponential equation dependence. Equation (11) shows the effect of sample weight/power level on D_{eff} of samples with the following coefficients: The estimated values of D_0 and E_a from the modified Arrhenius type exponential equation (Eq. 11) were $5.86 \times 10^{-9} m^2/s$ and 4.3778kW/kg, respectively.

This obtained value was similar the E_a of drying carrot slices with different infrared powers (4.247 kw/kg) (Doymaz, 2015).

$$D_{eff} = 5.86 \times 10^{-9} \exp\left[-\frac{4377.8m}{p}\right] \quad (11)$$

- *Energy consumption*

According to Table 2, energy consumption increased with increasing roasting temperature. Maximum and minimum energy consumption values were 1.752 and 1.112 kWh, at 200 and 160°C, respectively.

Infrared roasting is an inexpensive method consuming less energy than other roasting methods. Consumption data showed that the lowest energy needed for roasting soybeans with infrared was equal to 0.0905 kW h obtained at infrared power 200 W while the maximum energy consumption was 0.1287 kWh calculated at 300 W. In other words, the highest rate of energy expenditure was 1.42 times that of the lowest (Table 2).

As presented in Table 2, the lowest value of energy consumed in roasting soybeans was observed at 200 W and 120°C (0.552 kW h) and the highest value was at 130 and 160°C (0.924 kW h). In the combined hot air-infrared roasting method, energy consumption increased by increasing temperature while it decreased with increasing power. Similar findings were reported by Motevali *et al.* (2011) for drying of mushroom slices.

Comparison of three roasting methods in terms of energy showed that minimum energy was consumed in the infrared roasting method and maximum energy in hot air roasting with 0.0905 and 1.752 kW h, respectively. Therefore the infrared radiation might be considered as the best method for roasting of soybean in terms of energy consumption.

Conclusion

Roasting is one of the most important steps of the nut processing. In this study, roasting rate during thin layer roasting of soybeans was characterized. Soybeans roasting occurred in the falling rate period. Temperature and power dependences of the diffusivity coefficients were described by Arrhenius-type relationship and modified Arrhenius-type relationship, respectively. The page model showed the best results and good agreement with experimental data to explain the roasting behavior of soybean. With the increase of hot air temperature and infrared power, the effective moisture diffusivity increased. Infrared radiation might be considered as the best roasting method in terms of energy consumption.

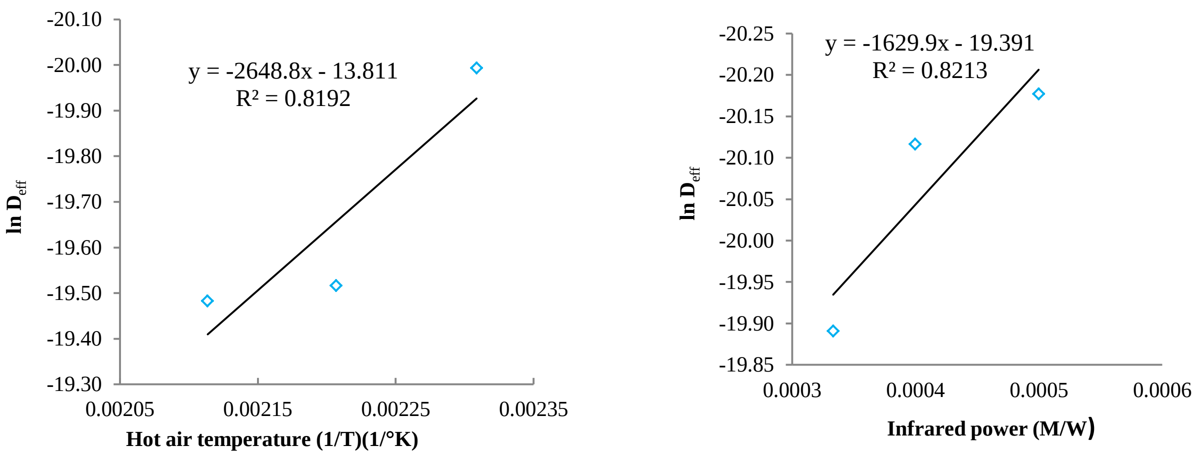

Fig. 4. Arrhenius relationship between D_{eff} and air temperature and modified Arrhenius relationship between D_{eff} and infrared power during roasting of soybean

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