doi: 10.17221/24/2014-RAE

Moisture and thermal diffusivity of lentil seed under convective infrared-microwave: Modelling with and without shrinkage

R.A. Chayjan, S.A. Radmard

Department of Biosystems Engineering, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran

Abstract

Chayjan R.A., Radmard S.A. (2016): **Moisture and thermal diffusivity of lentil seed under convective infrared-microwave: Modelling with and without shrinkage**. Res. Agr. Eng., 62: 129–140.

The effect of infrared radiation and microwave radiation on the moisture and thermal diffusivity characteristics of lentil seeds during infrared and microwave drying was investigated. Using mathematical equations, values and curves, moisture and thermal diffusivity were obtained. This study was to determine the moisture and thermal diffusivity of seed lentil with and without shrinkage at input temperatures 40°C and 60°C, infrared powers 1,000 W and 2,000 W and microwave power 270 W and 450 W, when the moisture content was reduced from 60 to 9% (d.b.). Drying rate was increased with increased air temperature, infrared radiation and microwave powers. Also drying rate decreased continuously with decreasing moisture content. The calculated values of moisture diffusivity by considering shrinkage were smaller than the values of moisture diffusivity without considering shrinkage. Moisture diffusivity with and without shrinkage decreased with decrease in moisture content of lentil seeds and thermal diffusivity with and without shrinkage decreased with increased moisture content. Both moisture and thermal diffusivity values decreased with increase in temperature.

Keywords: infrared radiation; equilibrium content; Fick's second equation; drying rate; dehydration

Grain legumes involve an important part of human diet in the world. Lentils (*Lens culinaris*) are a valuable nutrient due to plant protein. Lentil has the ability to overcome malnutrition problems of the poor due to being rich in protein (23–24%) (Rajput, Sarwar 1988). Fundamental data on moisture transfer of lentil seeds is needed for better control the product quality. During the drying process, water exerts from the cell and causes a decrease in cell wall tension. This decrease in tension causes shrinkage of the materials and leads to changes in shape and decrease in dimensions (Mayor, Sereno 2004; Hashemi et al. 2009).

The shrinkage phenomenon affects moisture and thermal diffusivity of the material, which is one of the main parameters in the drying process; it also has an influence on the drying rate (Senadeera et al. 2003). The theoretical determination of moisture diffusivities is difficult, because of the different physical and chemical structure and water content of material (Khir et al. 2011). Any design to indicate drying behaviour must inevitably pay attention to the physical parameters of the material such as thermal diffusivity and moisture diffusivity (Abbasi Souraki, Mowla 2008). Liquid and vapour diffusion is intended to be the initial mass transfer mechanism in drying grapes (Pahlavanzadeh et al. 2001).

Thermal diffusivity is an important transport exclusivity which is required in modelling and computations of transient heat transfer in basic food

doi: 10.17221/24/2014-RAE

processing operations. Both the moisture and thermal diffusivity depend largely on the temperature and the moisture content (Yang et al. 2002; Çağlar et al. 2009). A number of researchers have reported that there is an exponential relationship between diffusivity (moisture and thermal) and drying temperature (Roberts et al. 2008). But limited information has been published on the relationship between diffusivities and the moisture contents in foods (Çağlar et al. 2009). Hassini et al. (2007) stated that information processing based on analytical solution of a Fickian diffusion equation accounts for sample thickness reduction during drying. Janjai et al. (2007) stated diffusivities of different components of longan fruit and it was indicated that moisture diffusivities of the shell and seed coat are much lower than those of the flesh, seed stalk and seed. Axial and radial moisture diffusivity determined in cylindrical fresh green beans with and without shrinkage (Abbasi Souraki, Mowla 2008). Çağlar et al. (2009) determined the values of thermal diffusivity and moisture diffusivity and drying rate under different drying temperatures and moisture contents using data obtained from infrared drying for seedless grape. Mariani et al. (2008) estimated thermal diffusivity of foods at different drying temperatures. Engineers and researchers created several theoretical and experimental studies to obtain moisture diffusivity without shrinkage in lentils (Tang, Sokhansanj 1993; Tang et al. 1994). Scanlon et al. (2005) stated that the moisture diffusivity without shrinkage in infrared heat treatment lentils depend on the moisture content. Also Işık et al. (2011) studied on determination of drying kinetics of green laird lentil and selecting suitable model in microwave drying method. The kinetics of water absorption by lentils grown in Turkey was studied by a gravimetric method during soaking at 15, 25 and 40°C to determine moisture diffusivity without shrinkage of this selected lentil (Gürtas et al. 2001).

The aim of this study was determination of moisture and thermal diffusivities of lentil seed under various drying conditions with considering shrinkage phenomenon.

MATERIAL AND METHODS

Sample preparation. Fresh lentil (*Lens culinaris*) of Bile-Savar cultivar was provided from the Bu-Ali Sina University research farm, Hamedan, Iran. The samples were kept in a refrigerator at 4 ± 1°C until used. Their moisture content was determined using an air oven method. The initial moisture content was determined by drying the lentil sample in an air ventilated oven at 103°C for 72 h (ASAE 2007). The average moisture content was 60% (d.b.).

Experimental step. The samples were carried out in a laboratory infrared radiation fluidized bed dryer and microwave oven (Sharp R-196T; Sharp Electronic, Bangkok, Thailand). The drying tests were conducted at condition of 30°C and 30% relative humidity (RH).

Laboratory infrared radiation fluidized bed dryer is shown schematically in Fig. 1. The dryer consists of four infrared lamps (Philips 500 W; Philips Belgium NV, Flemish, Belgium) with 2,000 W power at the top of the chamber with 30 cm height. A backward centrifugal fan with an inverter (Vincker VSD2; ABB Co., Taipei, Taiwan) was used to control the fan speed and air velocity was adjusted at the value of 1.76 m/s. About 8 g of lentil seeds was putted in dryer chamber incombustible as a single layer and drying examination was started. Input air temperatures of 40 and 60°C and microwave power of 270 and 450 W were adjusted in the examinations.

A digital balance (AND GF-6000; AND Electronics, Tokyo, Japan) with 0.01 g accuracy was used to measure the sample weight and an infrared thermometer (Terminator, TIR 8863; Shenzhen Ever-

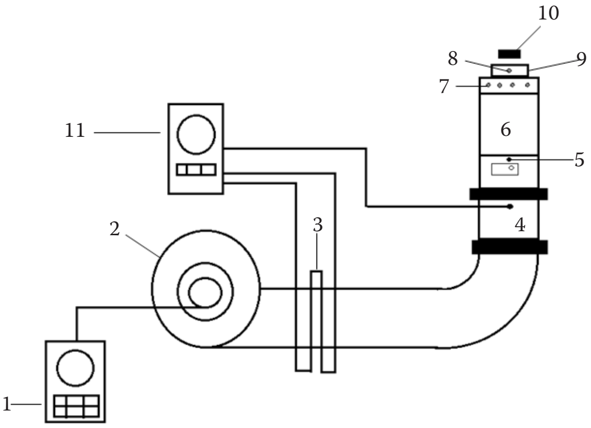

Fig. 1. Schematic diagram of laboratory infrared fluidized bed dryer

1 – inverter; 2 – fan and electrical motor; 3 –electric heater; 4 – mixing chamber; 5 – input air temperature recorder; 6 – drying chamber; 7 – infrared lamp; 8 – output air temperature recorder; 9 – air outlet; 10 – air velocity sensor; 11 – thermostat

best Machinery Industry Co., Shenzhen, China) was used to measure average temperature of lentil seeds. In order to determine the variations in volume of the lentil grains, the dimensions of the lentil grain in two directions were measured by means of a digital calliper (thickness, diameter) at the time intervals. Lentil drying process was continued until final moisture content received to 9% (d.b.). During drying process, equilibrium moisture content of different moisture contents of lentil seeds was calculated.

Theoretical principle. The method includes an analysis of the drying process by differential model. The differential equation based on Fick's second equation is (Kiranoudis et al. 1992):

$$\frac{\partial(\rho_d X)}{\partial t} = \nabla \times (D_{ef}\nabla(\rho_d X) \tag{1}$$

where:

X – moisture content (d.b.)
∇ – gradient
∂t – time variation (h)
D_{ef} – effective diffusivity (m^2/h)
ρ_d – density of dry solid (dry solid per volume of the moist material) that alerts with moisture content

By neglecting shrinkage, Eq. (1) is expressed as:

$$\frac{\partial X}{\partial t} = D_{efX}\nabla^2 X \tag{2}$$

where:

D_{efX} – moisture diffusivity without shrinkage (m^2/h)
∂X – moisture content variation (d.b.)
∂t – time variation (h)
X – moisture content (d.b.)

The boundary and initial conditions are as follows:

$t = 0, X = X_0$
$t = 0, z = 0, \partial X/\partial z = 0$
$t = 0, z = L, X = X_e$

where:

t – drying time (h)
X – moisture content (d.b.)
X_0 – initial moisture content (d.b.)
z – coordinate axis (d.b.)
∂X – moisture content variation (d.b.)
X_e – equilibrium moisture content (d.b.)
L – half thickness of grain (m)

For the path diffusion in the slab plate one may obtain (Crank 1975):

$$\frac{X - X_e}{X_0 - X_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\pi^2\frac{D_{efX}t}{L^2}\right) \tag{3}$$

where:

L – half thickness of lentil grain (m)
X – moisture content (d.b.)
X_0 – initial moisture content (d.b.)
X_e – equilibrium moisture content (d.b.)
t – time of drying (h)

In order to show the shrinkage effects, replacing $\rho_d = m_d/V$ in Eq. (1) could be showed (Park 1998; Uddin et al. 2004) as:

$$\frac{\partial((m_d/V)X)}{\partial t} = \nabla \times (D_{ef}\nabla((m_d/V)X) \tag{4}$$

where:

D_{ef} – effective diffusivity (m^2/h)
m_d – mass of dry solid (kg)
V – sample volume (mm^3)

This equation is changed to:

$$\frac{m_d\,\partial(X/V)}{\partial t} = m_d D_{ef}\nabla^2(X/V) \tag{5}$$

Replacing $Y = X/V$, the following equation is obtained:

$$\frac{\partial Y}{\partial t} = D_{efY}\nabla^2 Y \tag{6}$$

where:

D_{efY} – moisture diffusivity with shrinkage (m^2/h), with the following initial and boundary conditions:

$t = 0, Y_0 = X_0/V_0$
$t > 0, z = 0, \partial Y/\partial z = 0$
$t > 0, z = L, Y_e = X_e/V_e$

$$\frac{Y - Y_e}{Y_0 - Y_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\pi^2\frac{D_{efY}t}{L^2}\right) =$$
$$= \frac{8}{\pi^2}\left[\exp\left(-\pi^2\frac{D_{efY}t}{L^2}\right) + \frac{1}{9}\exp\left(-\pi^2\frac{D_{efY}t}{L^2}\right) +\right.$$
$$\left. + \frac{1}{25}\exp\left(-\pi^2\frac{D_{efY}t}{L^2}\right) + \cdots\right] \tag{7}$$

Considering the first term, following equation could be showed as:

$$\frac{Y - Y_e}{Y_0 - Y_e} = \frac{8}{\pi^2}\left[\exp\left(-\pi^2\frac{D_{efY}t}{L^2}\right)\right] \tag{8}$$

where:

V_0 – sample volume (mm^3)
V_e – grain volume in equilibrium moisture content (mm^3)

Y_0 – ratio of initial moisture content of grain to initial volume content of grain ($\text{kg}_{\text{water}}/\text{kg}_{\text{dry solid}}\ \text{mm}^3$)
Y_e – ratio of equilibrium moisture content of grain to the grain volume in its equilibrium moisture content ($\text{kg}_{\text{water}}/\text{kg}_{\text{dry solid}}\ \text{mm}^3$)

The calculation of the lentil volume was based on the following equation (Scanlon et al. 2005):

$$V = 2V_s \tag{9}$$

$$V_s = \frac{1}{3}[\pi^2 b^2 (3r - b)] \tag{10}$$

$$r = \frac{b}{2} + \frac{a^2}{8b} \tag{11}$$

where:
$2V_s$ – equal to the original volume V of an average lentil grain (mm^3)
r – function of thickness and diameter
b, a – half thickness (mm) and diameter (mm) of a lentil grain

Equilibrium moisture content is the moisture content that lentils will eventually reach under a given air condition. Equilibrium moisture content values (X_e) were obtained from the moisture isotherms reported by Samaniego-Esguerra et al. (1991):

$$X_e = \frac{A'B'C'(RH)}{[1 - B'(RH)][1 - B'(RH) + B'C(RH)]} \tag{12}$$

$$B' = B \exp\left(\frac{h_1}{R.T}\right) \tag{13}$$

$$C' = C \exp\left(\frac{h_2}{R.T}\right) \tag{14}$$

where:
X_e – equilibrium moisture content (% d.b.)
RH – relative humidity (%)
A, B, C, h_1, h_2 – coefficients
T – absolute temperature (K)
$R = 8.314$ – universal gas constant (J/mol K)

Thermal diffusivity. This study is one of transient heat conduction in a finite slab with thickness of L and the following initial and boundary conditions:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}, 0 \leq x \leq L \text{ for } t > 0 \tag{15}$$

$$V_s = \frac{1}{3}[\pi^2 b^2 (3r - b)] \tag{16}$$

where:
T_s – ambient temperature (°C)
k – thermal conductivity (W/mK)
H – effective heat transfer coefficient ($\text{W/m}^2\text{K}$)
T_i – initial temperature (°C)
α – thermal diffusivity (m^2/h)

The differential equation based on Eq. (15) for the path diffusion in the slab plate one may obtain is (Crank 1975):

$$\frac{T(x,t) - T_s}{T_i - T_s} = \sum_{n=0}^{n=\infty} a_n \exp\left(-\frac{n^2\pi^2\alpha t}{L^2}\right) \sin\left(\frac{n\pi x}{L}\right) \tag{17}$$

Where for a square wave a finite body is , then Eq. (17) is expressed as:

$$\frac{T(x,t) - T_s}{T_i - T_s} = \sum_{n=0}^{n=\infty} \frac{4}{n^2\pi^2}\left[\exp\left(-\pi^2 \frac{\alpha t}{L^2}\right) \sin\left(\frac{\pi x}{L}\right) + \right.$$
$$\left. + \frac{1}{9} \exp\left(-\pi^2 \frac{\alpha t}{L^2}\right) \sin\left(\frac{3\pi x}{L}\right) + \cdots\right] \tag{18}$$

Considering the first term, the following equation could be showed as:

$$\frac{T(x,t) - T_s}{T_i - T_s} = \frac{4}{\pi^2} \exp\left(-\pi^2 \frac{\alpha t}{L^2}\right) \tag{19}$$

RESULTS AND DISCUSSION

Drying characteristics

Moisture content and drying rate were varied with infrared radiation powers, microwave powers and temperature levels. Variations in the moisture content and drying rate at different conditions of infrared radiation-microwave drying are shown in Figs 2 and 3. Infrared and microwave radiation energy is transferred from the heating element to the product surface without heating the surrounding air. The radiation impinges on the material and penetrates it and then is converted to sensible heat. With increased infrared and microwave powers, the more heat is generated which increases lentil temperature. The results showed that moisture content of lentil grain decreased continuously with drying time (Chayjan et al. 2013) and drying rate decreased continuously with decreasing moisture content (Çağlar et al. 2009). During the drying process, moisture content reduced from 60 to 9% because moisture is in liquid phase form in capillary vessels of lentils seeds. All capillary vessels in lentils seeds have different width. The vapour occurs of these capillary vessels that is transported moisture inner lentil to lentils seed surface during

doi: 10.17221/24/2014-RAE

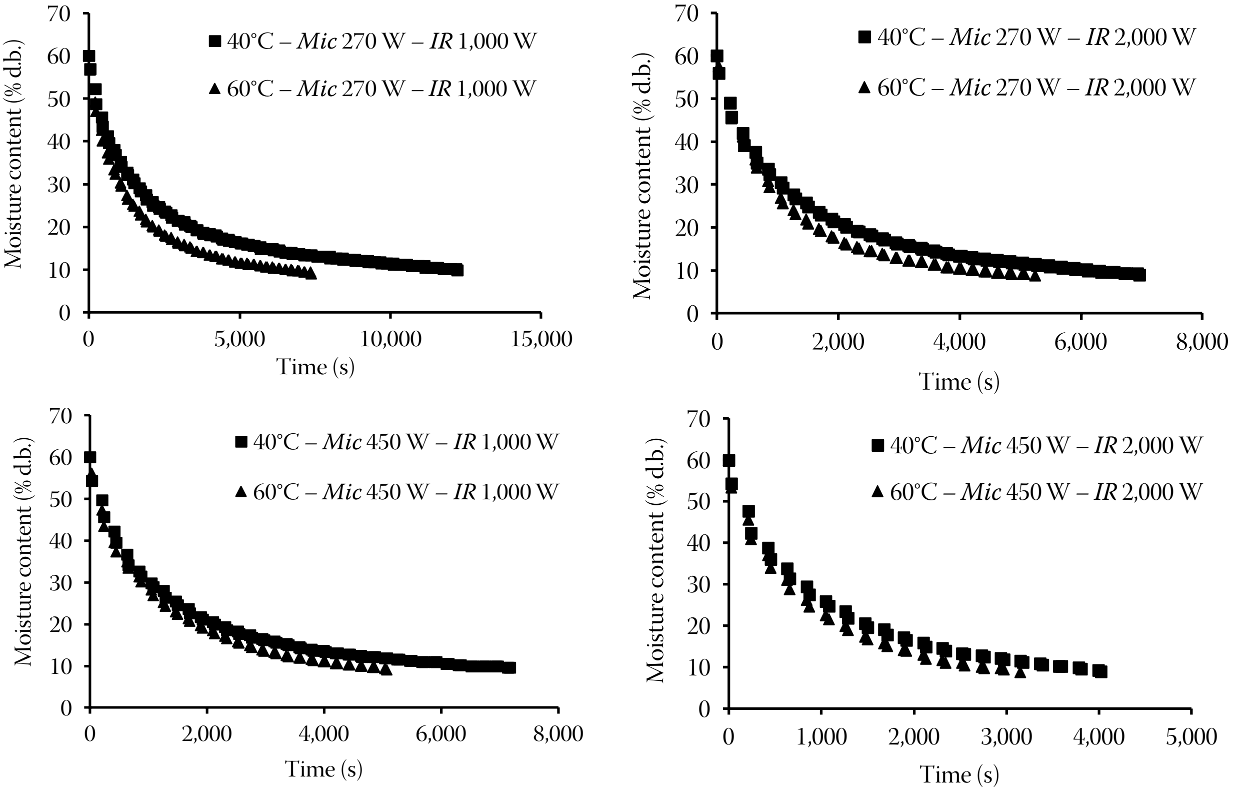

Fig. 2. Moisture content variation of lentil seeds at input airdifferent temperatures and different microwave and infrared radiation powers
Mic –microwave power; *IR* –infrared radiation power

drying. Vapour transport velocity in a narrow capillary vessel is higher than a wide capillary vessel (Pickles 2003; Çağlar et al. 2009). Another cause is hygroscopic shrinkage; reducing moisture content resulted in a decrease in the permeability of the seedcoat of lentil. Similar results were reported in moisture-absorption characteristics of laird lentils and hardshell seeds (Tang et al. 1994), moisture diffusivity in laird lentil seed components (Tang, Sokhansanj 1993), drying kinetic and physical properties of green laird lentil in microwave drying (Işık et al. 2011) and the physical properties of micronised lentils as a function of tempering moisture (Scanlon et al. 2005).

At infrared power *IR* = 2,000 W, microwave power *Mic* = 450 W and air temperature *T* = 60°C had most influence because high infrared and microwave power cause high evaporation from seedcoat of lentil. The infrared power and microwave power had significant effects on the drying time of the lentil seeds, particularly in high temperature conditions. Drying rate decreased with decrease in moisture content of lentil seeds and drying rate is increased with increase in air temperature, infrared power and microwave power. The increase in evaporation rate with temperature was stated in (Çağlar et al. 2009). With decreasing moisture content of lentil seed, evaporation rate from the surface of lentil grain is more difficult and then drying rate is carried out very slow at the end of drying process. Diameter and thickness of the grain decrease as moisture content decreases. Similar results were reported in drying kinetic and physical properties of green laird lentil in microwave drying (Işık et al. 2011).

Shrinkage

The results shown in Fig. 4 indicate that with increasing temperature shrinkage value increases (Hatamipour, Mowla 2003; Hashemi et al. 2009). Shrinkage value at 60°C is higher than at 40°C. The radiation penetrates the exposed material and the energy of radiation is converted into heat (Hebbar, Rostagi 2001), then with increasing power of infrared radiation and microwave, lentil grain temperature increased due to the absorption

doi: 10.17221/24/2014-RAE

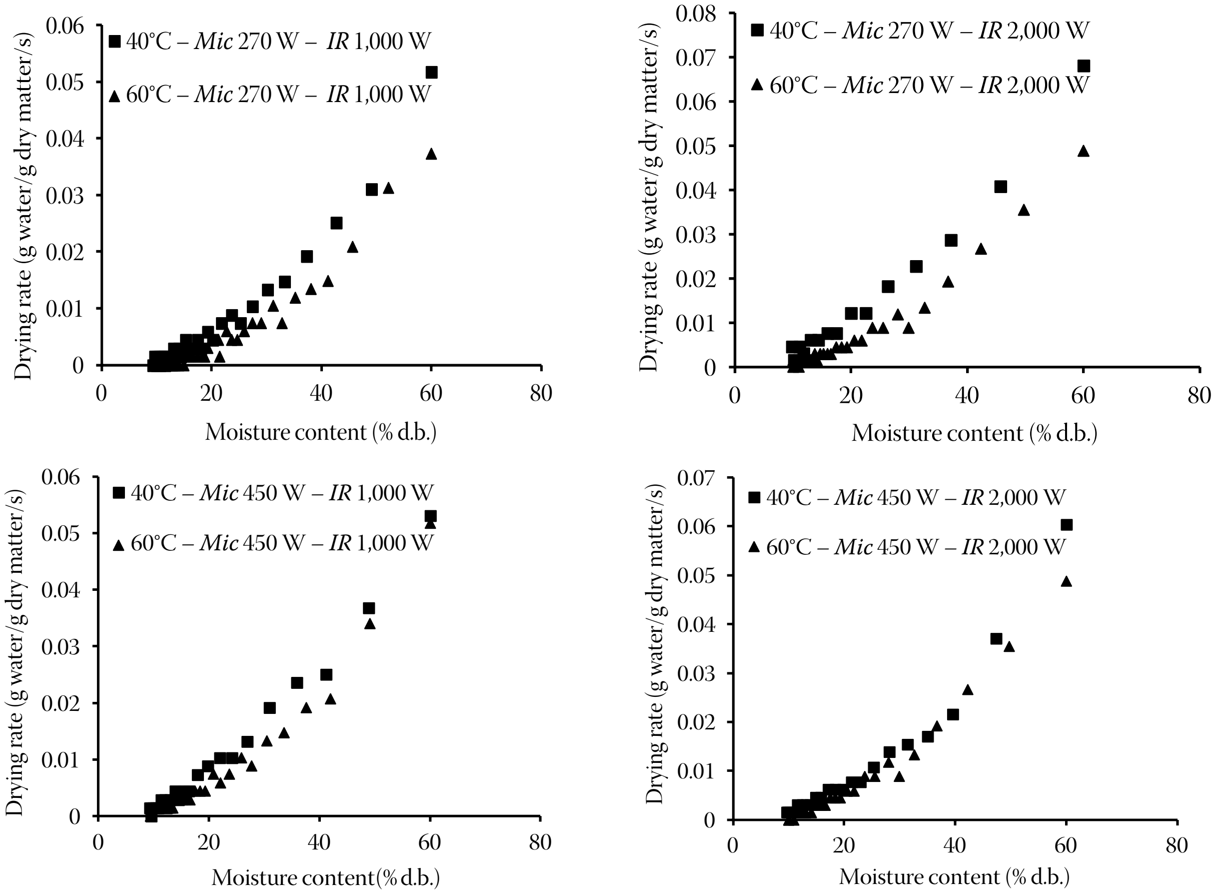

Fig. 3. Drying rate of lentil seeds at input airdifferent temperatures and different microwave and infrared radiation powers *Mic* –microwave power, *IR* –infrared radiation power

of radiation. The results showed that in condition of *Mic* = 450 W, *IR* = 2,000 W and *T*= 60°C max. Shrinkage was achieved. Shrinkage process produces a variation in the distance required for the movement of water molecules. Raising the temperature increases the movement of water molecules in the lentil grain and makes the distance between the molecules increase. Increasing temperature also causes expanding of structure and provides large area to volume ratio for good heat and mass transfer facilitating the water transport (Aroldo, Murr 2006).

Moisture diffusivities

Before calculating the moisture diffusivity, equilibrium moisture content of lentil grain should be calculated. Several drying experiments were followed under different operating conditions (air temperatures, infrared radiation and microwave power) and the changes in volume of drying sample were determined from equations Eqs (9–11) at drying process time. Equilibrium moisture content was obtained from Eqs (12–14) where Menkov (2000) reported values of A', B' and C' (dimensionless parameters in Eqs (12–14) are 9.12, 0.32 and 0.0007, respectively and the values of h_1 and h_2 are 1,937.14 and 24,419.87, respectively. Table 1 shows equilibrium moisture content at ambient air temperature and relative humidity of 30°C and 30%, respectively and Y_e at different input air temperatures and different powers of microwave and infrared radiation.

Variations of moisture diffusivity with and without shrinkage versus moisture content are shown in Fig. 5; in consequence, moisture diffusivity of the lentil seeds decreased versus moisture content. The calculated values of moisture diffusivity with shrinkage are smaller than without shrinkage. This shows that the effect of moisture diffusivity calculated without shrinkage overestimates the transport of mass by diffusion. This fact was also

doi: 10.17221/24/2014-RAE

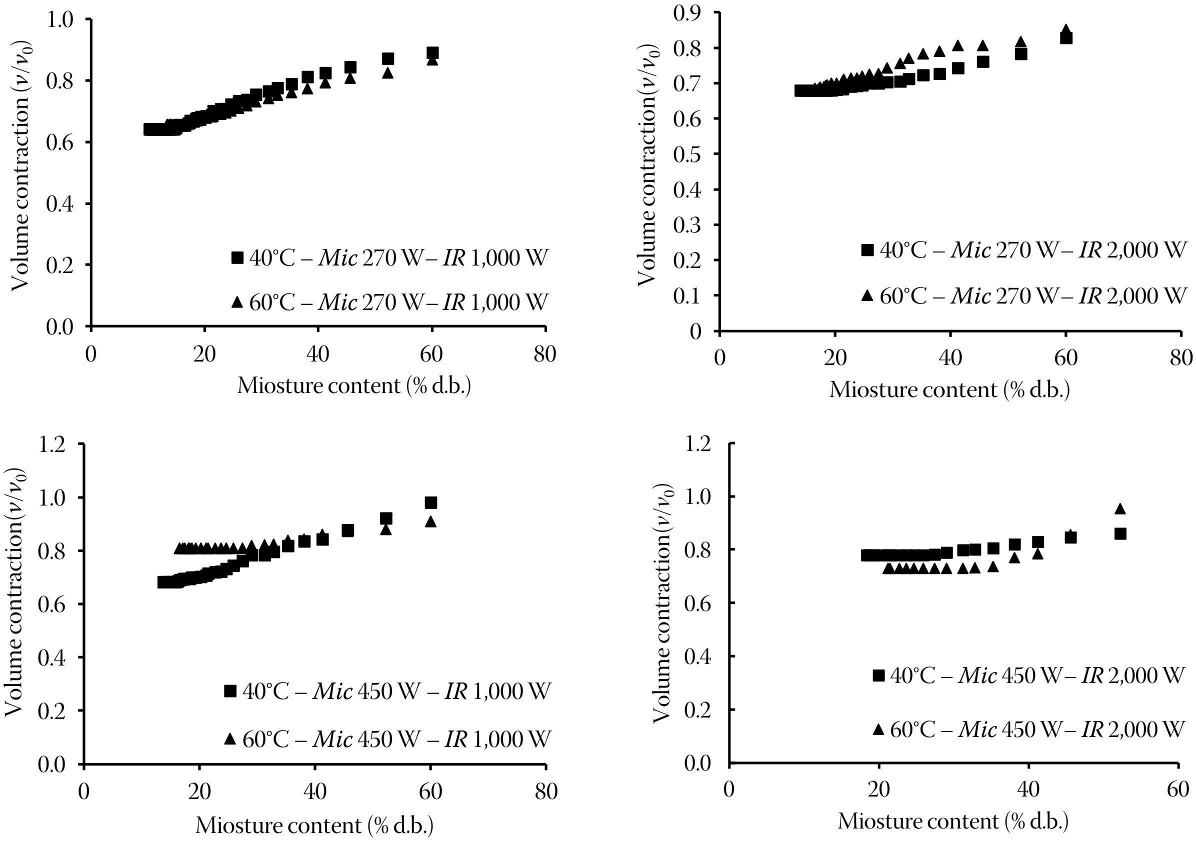

Fig. 4. Volume contraction variation of lentil seeds at input airtemperatures, microwave and infrared radiation powers *Mic* –microwave power, *IR* –infrared radiation power

observed by Abbasi Souraki and Mowla (2008) for axial and radial moisture diffusivity in cylindrical fresh green beans in a fluidized bed dryer. Also Arevalo-Pinedo and Murr (2006) reported similar results for vacuum drying of pumpkin. Moisture diffusivity at 60°C was higher than at 40°C; also high infrared and microwave power caused drying in less time and higher evaporation from lentil grains (Fig. 5). At first, moisture diffusivity increased because vapour phase diffusivity of lentil increased. When total diffusivity values are determined with liquid phase diffusivity in case of high moisture content values, it is determined with vapour phase diffusivity in low moisture. Total diffusivity decreases with decreasing moisture content, because the decrease in vapour phase diffusivity is greater than the increase in liquid phase diffusivity (Çağlar et al. 2009). Moisture diffusivity decreased when the moisture content was reduced from 60 to 9% (d.b.); other causes are shrinkage of the seedcoat of lentil and resistance of a composite material consisting of the seedcoat and cotyledons of lentil. Seedcoat of lentil mainly ruled in reduction rate of moisture diffusivity. Variation in seedcoat of lentil properties may significantly affect moisture evaporation rates of lentil. Similar results

Table 1. Ratio of equilibrium moisture content of grain to the grain volume in its equilibrium moisture content (Y_e) at different input temperatures and different powers of microwave (*Mic*) and infrared radiation (*IR*) at relative humidity 30%, ambient temperature 30°C and with equilibrium moisture content 8.6% d.b.

Input temperature (°C)	40				60			
Mic (W)	270		450		270		450	
IR (W)	1,000	2,000	1,000	2,000	1,000	2,000	1,000	2,000
Y_e ($kg_{water}/kg_{dry\ solid}\ m^3$)	0.15	0.18	0.17	0.15	0.15	0.17	0.16	0.13

doi: 10.17221/24/2014-RAE

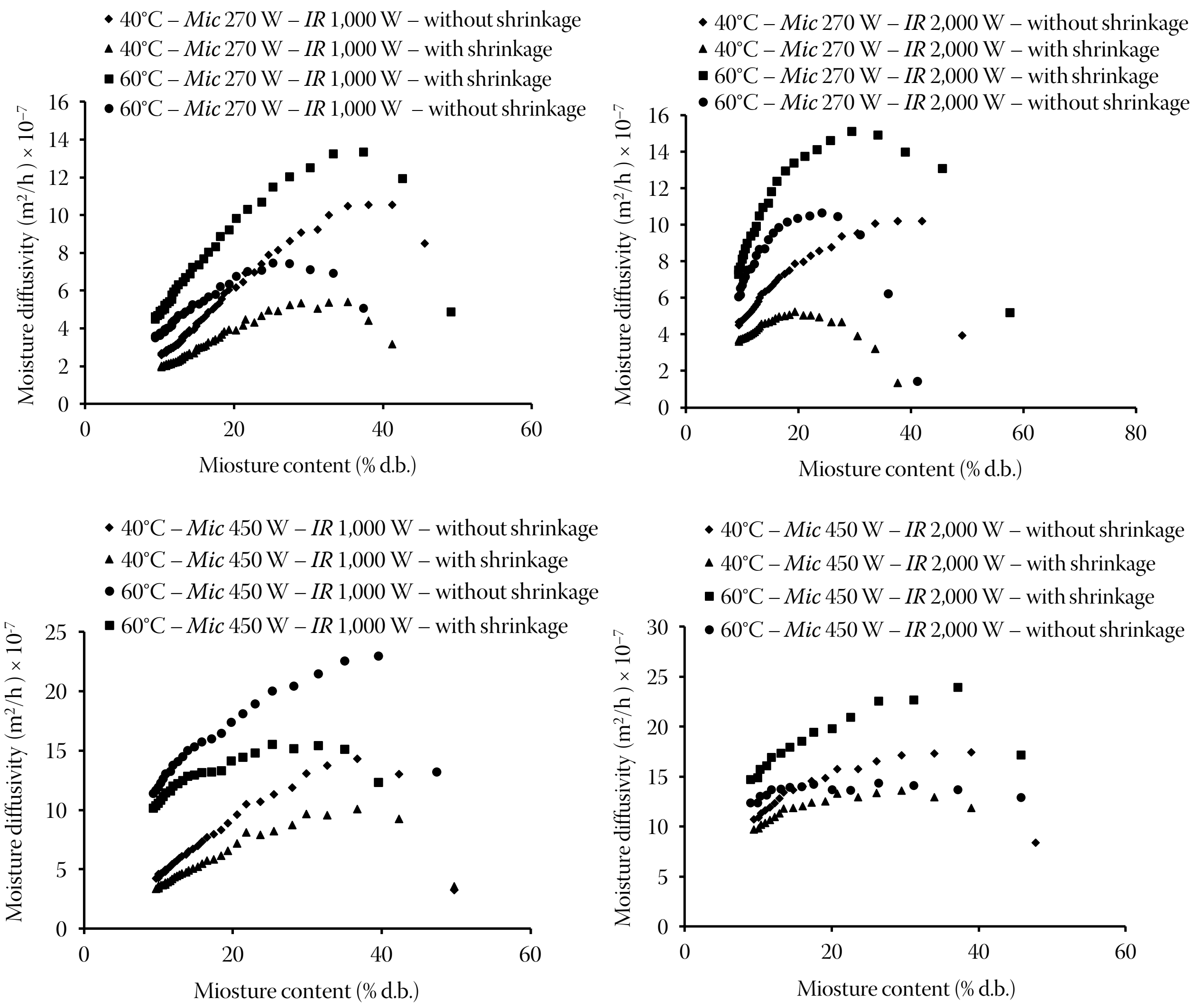

Fig. 5. Moisture diffusivity of lentil seeds at input air different temperatures and different powers of microwave and infrared radiation including

Table 2. Values of moisture diffusivity without shrinkage (D_{efX}) and with shrinkage (D_{efY}) in other researches under different powers of microwave (*Mic*) and infrared radiation (*IR*)

Material	Temperature (°C)	Range of D_{efX} ($\times 10^{-6}$ m²/h)	Range of D_{efY} ($\times 10^{-6}$ m²/h)	Reference
Lentil	30–50	10	–	(Tang, Sokhansanj 1993)
Lentil	40	10.8	–	(Scanlon at al. 2005)
Fresh lentil	45–60	10.9–64	–	(Karatas 1997)
Lentil	40°C, *IR* = 1,000 W, *Mic* = 270 W	8.4	4.80	present work
	40°C, *IR* = 2,000 W, *Mic* = 270 W	11.3	9	
	40°C, *IR* = 1,000 W, *Mic* = 450 W	10.6	8.4	
	40°C, *IR* = 2,000 W, *Mic* = 450 W	26.8	24.3	
	60°C, *IR* = 1,000 W, *Mic* = 270 W	11.2	8.7	
	60°C, *IR* = 2,000 W, *Mic* = 270 W	18.2	14.7	
	60°C, *IR* = 1,000 W, *Mic* = 450 W	28.5	25.4	
	60°C, *IR* = 2,000 W, *Mic* = 450 W	36.8	31	

doi: 10.17221/24/2014-RAE

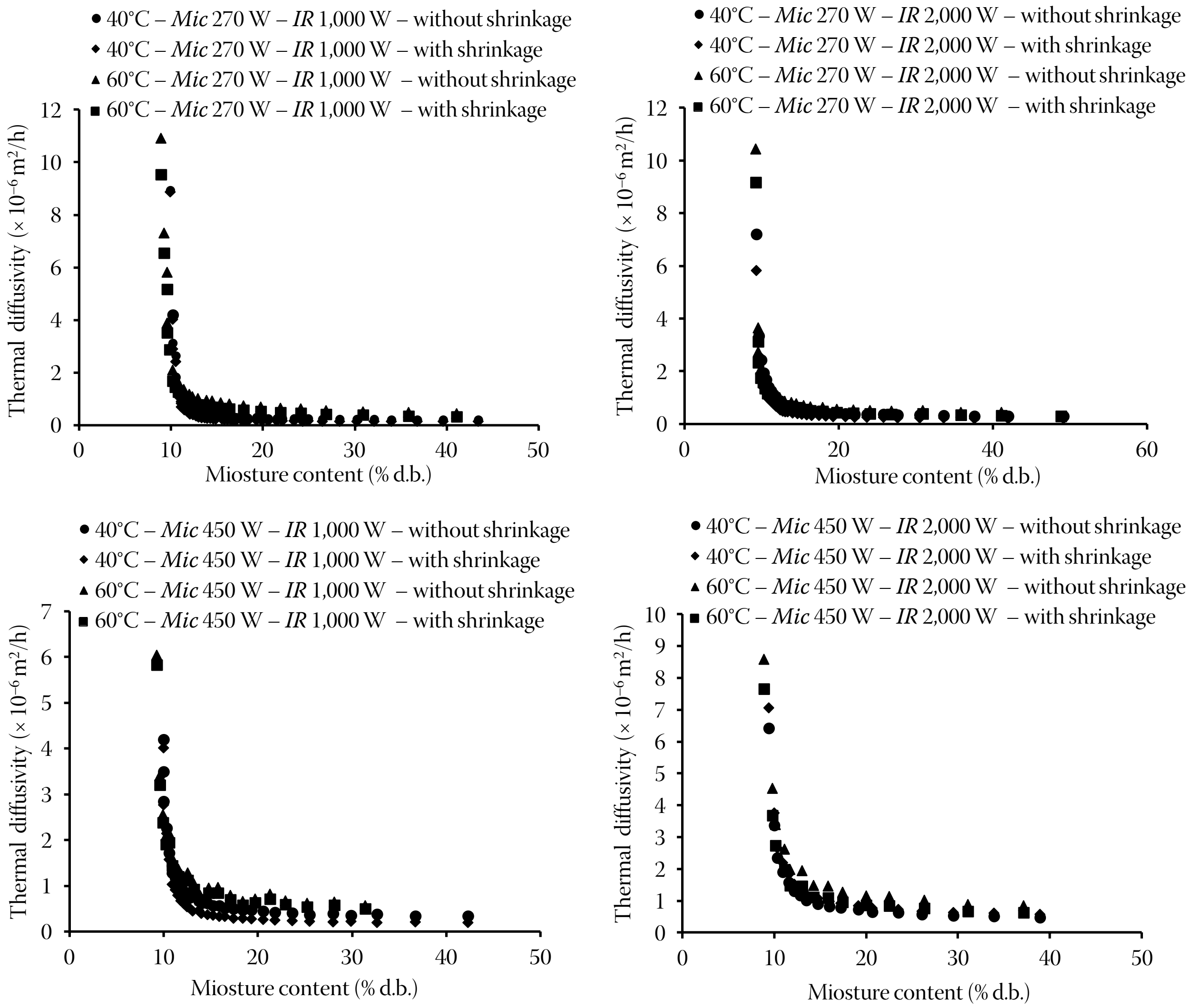

Fig. 6. Thermal diffusivity of lentil seeds at input air different temperatures and different powers of microwave and infrared radiation including

Mic –microwave power, *IR* – infrared radiation power

were reported in moisture diffusivity in laird lentil seed components (Tang, Sokhansanj 1993) and moisture-absorption characteristics of laird lentils and hardshell seeds (Tang et al. 1994).

At the start of drying process, influence of microwave power was higher than infrared radiation, because at the start of the process, lentil grains were exposed to temperature about 95°C. In Fig. 5a at 40°C, when moisture diffusivity without shrinkage increased from 2.12×10^{-7} to 2.63×10^{-7} then moisture diffusivity decreased to 0.84×10^{-7} and when moisture diffusivity with shrinkage increased from 0.79×10^{-7} to 1.35×10^{-7} then moisture diffusivity decreased to 0.48×10^{-7}. Similar trends were found for other conditions, with and without shrinkage (Fig 5b–d).

Table 2 shows values of moisture diffusivity without shrinkage (D_{efX}) and moisture diffusivity with shrinkage (D_{efY}) estimated by other investigators and present work. The estimated values of moisture diffusivity without shrinkage at 40°C in three cases (*IR* = 1,000 W and *Mic* = 270 W, *IR* = 2,000 W and *Mic* = 270 W, *IR* = 1,000 W and *Mic* = 450 W) are close to each other. The moisture diffusivities without shrinkage estimated in this work are in agreement with those proposed by Tang and Sokhansanj (1993), Karatas (1997) and Scanlon et al. (2005). At 40°C, *IR* = 2,000 W and *Mic* = 450 W had higher values of moisture diffusivities without shrinkage, because the absorption microwave and infrared radiation cause increase in temperature at lentil as a result of moisture diffusivity without shrink-

Table 3. Values of thermal diffusivity (α) of several products in number of other researches under different powers of microwave (*Mic*) and infrared radiation (*IR*)

Material	Temperature (°C)	Range of α without shrinkage (×10^{-6} m^2/h)	Range of α with shrinkage (×10^{-6} m^2/h)	Reference
Borage seed	6–20	8.35–11.44	–	(Yang et al. 2002)
Barley				
cv. Kavir	25	5.65–1.18	–	(Nouri Jangi et al. 2011)
cv. Nosrat	25	5.28–2.13	–	
Red lentil		3.40–3.01	–	(Kara et al. 2012)
Red lentil		7.74–5.94	–	(Gharibzahedi et al. 2013)
Lentil	40°C, *IR* = 1,000 W, *Mic* = 270 W	0.2	0.12	present work
	40°C, *IR* = 2,000 W, *Mic* = 270 W	0.29	0.19	
	40°C, *IR* = 1,000 W, *Mic* = 450 W	0.34	0.19	
	40°C, *IR* = 2,000 W, *Mic* = 450 W	0.55	0.47	
	60°C, *IR* = 1,000 W, *Mic* = 270 W	0.42	0.3	
	60°C, *IR* = 2,000 W, *Mic* = 270 W	0.4	0.3	
	60°C, *IR* = 1,000 W, *Mic* = 450 W	0.56	0.5	
	60°C, *IR* = 2,000 W, *Mic* = 450 W	0.84	0.63	

age, compared to other cases (*IR* = 1,000 W and *Mic* = 270 W, *IR* = 2,000 W and *Mic* = 270 W, *IR* = 1,000 W and *Mic* = 450 W). The D_{efY} value can be calculated based on D_{efX} as follows:

$$D_{efY} = 1.069D_{efX} + 0.209R^2 = 0.9915 \qquad (20)$$

Thermal diffusivity

Thermal diffusivity versus moisture content increased with increasing temperature during drying process and thermal diffusivity decreased with increasing moisture content (Fig. 6). This fact was also observed by Çağlar et al. (2009) for thermal diffusivity of seedless grape under infrared drying.

With increasing power of infrared radiation and microwave power, lentil grain temperature increased due to the absorption of radiation. By attention to higher conversion value from water to vapour at higher temperature, vapour phase diffusivity is increased in the first period drying. When thermal diffusivity values are determined with liquid phase diffusivity in high moisture content values, it is determined with vapour phase diffusivity in low moisture content. Increasing temperature causes high evaporation from seedcoat of lentil and thus reduces vapour phase diffusivity. The thermal diffusivity decreases with decreasing moisture content, because the decrease in vapour phase diffusivity is greater than the increase in liquid phase diffusivity (Jood et al. 1998; Çağlar et al. 2009). Because of different moisture in components of lentil, the curve of thermal diffusivity of lentil seed is behaviour of natural logarithm at drying time. Also thermal diffusion model considering thickness changes of lentil seeds are effect overestimates.

In Fig. 6a at 40°C, thermal diffusivity without shrinkage decreased from 8.92 × 10^{-6} m^2/h to 0.2 × 10^{-6} m^2, h and thermal diffusivity with shrinkage decreased from 8.85 × 10^{-6} m^2/h to 0.12 × 10^{-6} m^2/h. Similar trends were observed for other conditions, with and without shrinkage (Fig. 6b– d).

Table 3 shows thermal diffusivity with and without shrinkage values estimated by other investigators and present work. The estimated values of thermal diffusivity without shrinkage in the literature are different, because the lentil seeds used in this study were tested after harvesting but in Kara et al. (2012) and Gharibzahedi et al. (2013) they were tested after several months of storage. Storage of lentil causes biological processes. Effects of storage on the seed breakage, germination and cooking quality of lentils were further studied by

doi: 10.17221/24/2014-RAE

investigators. Storage of lentils increased breakage sensitivity and reduced cooking quality (Yadav et al. 2007). Also temperature and initial moisture content effect on thermal diffusivity were observed (Yang et al. 2002; Çağlar et al. 2009). Temperature and initial moisture content of lentil seed in this study were more than temperature and initial moisture content of red lentil seed in other studies. The cultivar of lentil seeds used in this study was different from red lentils used by Kara et al. (2012) and Gharibzahedi et al. (2013).The effective thermal diffusivity without shrinkage (α_{efY}) can be calculated based on effective thermal diffusivity with shrinkage (α_{efX}) as follows:

$$\alpha_{efY} = 0.837\alpha_{efX} - 0.055 R^2 = 0.9478 \quad (21)$$

CONCLUSION

Drying rate and volume contraction decreased with decreasing moisture content of lentil seeds. Drying rate and volume contraction at 60°C were more than at 40°C. Increasing infrared radiation and microwave power caused increase in drying rate and volume contraction. Moisture diffusivity, with and without shrinkage decreased with decrease in moisture content of lentil seeds, and thermal diffusivity with and without shrinkage decreased with increasing moisture content. Both moisture and thermal diffusivity with and without shrinkage values increased with increase in temperature.

References

Abbasi Souraki B., Mowla D. (2008): Axial and radial moisture diffusivity in cylindrical fresh green beans in a fluidized bed dryer with energy carrier: Modeling with and without shrinkage. Journal of Food Engineering, 88: 9–19.

Arévalo-Pinedo A., Murr F.E.X. (2006): Kinetics of vacuum drying of pumpkin (*Cucurbita maxima*): Modeling with shrinkage. Journal of Food Engineering, 76: 562–567.

ASAE (2007): ASAE Standard S352.2: Moisture measurement-unground grain and seeds, 54th Ed. St. Joseph, USA.

Chayjan R.A., Tabatabaei S.M., Rahimi F. (2013): Modeling infrared-convective drying of pistachio nuts under fixed and fluidized bed conductions. Journal of Food Processing and Preservation, 38: 1224–1233. doi: 10.1111/jfpp.12083.

Crank J. (1975): The mathematics of diffusion (2nd Ed.). Oxford, Oxford University Press.

Çağlar A., Toğrul I.T., Toğrul H. (2009): Moisture and thermal diffusivity of seedless grape under infrared drying. Food and Bioproducts Processing, 87: 292–300.

Gharibzahedi S.M.T., Ghahderijani M., Sadat Lajevardi Z.h. (2014): Specific heat, thermal conductivity and thermal diffusivity of red lentil seed as a function of moisture content. Journal of Food Processing and Preservation, 38: 1807–1811. doi: 10.1111/jfpp.12151.

Gürtas F., Ak M., Evranuz E. (2001): Water diffusion coefficients of selected legumes grown in turkey as affected by temperature and variety. Turk Journal Agriculture, 25: 297–304.

Hashemi G., Mowla D., Kazemeini M. (2009): Moisture diffusivity and shrinkage of broad beans during bulk drying in an inert medium fluidized bed dryer assisted by dielectric heating. Journal of Food Engineering, 92: 331–338.

Hassini L., Azzouz S., Peczalski R., Belghith A. (2007): Estimation of potato moisture diffusivity from convective drying kinetics with correction for shrinkage. Journal of Food Engineering, 79: 47–56.

Hatamipour M.S., Mowla D. (2003): Correlations for shrinkage, density and diffusivity for drying of maize and green peas in a fluidized bed with energy carrier. Journal of Food Engineering, 59: 221–227.

Hebbar H.U., Rostagi N.K. (2001): Mass transfer during infrared drying of cashew kernel. Journal Food Engineering, 47: 1–5.

Işik E., Izli N., Bayram G., Turgut I. (2011): Drying kinetic and physical properties of green laird lentil (*Lens culinaris*) in microwave drying. African Journal of Biotechnology, 10: 3841–3848.

Janjai S., Bala B.K., Lamlert N., Mahayothee B., Haewsungcharern M., Muhlbauer W., Muller J. (2007): Moisture diffusivity determination of different parts of longan fruit. International Journal of Food Properties, 10: 471–478.

Jood S., Bishnoi S., Sharma A. (1998): Chemical analysis and physico-chemical properties of chickpea and lentil cultivars. Nahrung, 42: 71–74.

Kara M., Boydas M.G., Kara Y.A., Ozturk I. (2012): The effect of moisture content on the thermal properties of red lentil. American Society of Agricultural and Biological Engineers, 55: 2301–2306.

Karatas S. (1997): Determination of moisture diffusivity of lentil seed during drying. Drying Technology: An International Journal, 15: 183–199.

Kiranoudis C.T., Maroulis Z.B., Marinos-Kouris D. (1992): Model selection in air drying of foods. Drying Technology, 10: 1097–1106.

Khir R., Pan Z., Salim A., Hartsough B.R., Mohamed S. (2011): Moisture diffusivity of rough rice under infrared radiation drying. LWT – Food Science and Technology, 44: 1126–1132.

doi: 10.17221/24/2014-RAE

Mariani V.C., De Limab A.G.B., Coelho L.D.S. (2008): Apparent thermal diffusivity estimation of the banana during drying using inverse method. Journal of Food Engineering, 85: 569–579.

Mayor L., Sereno A.M. (2004): Modeling shrinkage during convective drying of food materials: a review. Journal of Food Engineering, 61: 373–386.

Menkov N.D. (2000): Moisture sorption isotherms of lentil seeds at several temperatures. Journal of Food Engineering, 44: 205–211.

Nouri Jangi A., Mortazavi S.A., Tavakoli M., Ghanbari A., Tavakolipour H., Haghayegh G.H. (2011): Comparison of mechanical and thermal properties between two varieties of barley (*Hordeum vulgare* L.) grains. Australian Journal of Agricultural Engineering, 2: 132–139.

Pahlavanzadeh H., Basiri A., Zarrabi M. (2001): Determination of parameters and pretreatment solution for grape drying. Dry Technology, 19: 217–226.

Park K.J. (1998): Diffusional model with and without shrinkage during salted fish muscle drying. Drying Technology, 16: 889–905.

Pickles C.A. (2003): Drying kinetics of nickeliferous limonitic laterite ores. Miner Engineering, 16: 1327–1338.

Rajput M.A., Sarwar G. (1988). Development of high yielding mungbean mutants in Pakistan. Food Legumes Coarse Seed, 5: 3.

Roberts J.S., Kidd D.R., Padilla-Zakour O. (2008): Drying kinetics of grape seeds. Journal of Food Engineering, 89: 460–465.

Samaniego-Esguerra C.M., Boag I.F., Robertson G.L. (1991): Comparison of regression methods for fitting the GAB model to the moisture isotherms of some dried fruit and vegetables. Journal of Food Engineering, 13: 115–133.

Scanlon G.M., Cenkowski S., Segall K., Arntfie L.D.S. (2005): The physical properties of micronised lentils as a function of tempering moisture. Biosystems Engineering, 92: 247–254.

Senadeera W., Bhandari B., Young G., Wijesinghe B. (2003): Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying. Journal of Food Engineering, 58: 277–283.

Sharma G.P., Verma R.C., Pathare P.B. (2005): Thin-layer infrared radiation drying of onion slices, Journal of Food Engineering, 67: 361–366.

Tang J., Sokhansanj S. (1993): Moisture diffusivity in laird lentil seed components. American Society of Agriculture Engineering, 36: 1791–1798.

Tang J., Sokhansanj S., Sosulski F. (1994): Moisture-Absorption characteristics of laird lentils and hardshell seeds. American Association Cereal Chemists, 71: 423–428.

Uddin M.S., Hawlader M.N.A., Hui X. (2004): A comparative study on heat pump, microwave and freeze drying of fresh fruits. In: Proceedings of the 14th International Drying Symposium, São Paulo, Brazil: 2035–2042.

Yang W., Sokhansanj S., Tang J., Winter P. (2002): Determination of thermal conductivity, specific heat and thermal diffusivity of borage seeds. Biosystems Engineering, 82: 169–176.

Yadav S.S., Mcneil D.L., Stevenson P.C. (2007): Lentil An Ancient Crop for Modern Times. Dordrecht, Springer, 397–398.

Received for publication September 21, 2014
Accepted after corrections May 11, 2015

Corresponding author:

Reza Amiri Chayjan, Department of Biosystems Engineering, Faculty of Agriculture, Bu-Ali Sina University, Hamedan 6517833131, Iran; e-mail: amirireza@yahoo.com