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MODELLING MOISTURE DIFFUSIVITY AND ENERGY CONSUMPTION OF CANTALOUPE SEEDS IN FIXED AND FLUIDIZED BED CONDITIONS

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ABSTRACT

Background. The main goal in cantaloupe seed drying is the reduction of its moisture content to a safe level, allowing storage in a long period of time. Fluidized bed dryer is a drying process with better heat and mass transfer and shorter drying time. This method is a gentle and uniform drying procedure. Fluidized bed is suitable for sensitive and high moisture materials. Drying parameters of moisture diffusivity and energy are vitally important in modelling and optimizing of the seed dryer system.
Material and methods. This study investigated thin layer characteristics of cantaloupe seeds under fixed, semi fluidized and fluidized bed drying with initial moisture content about 61.99% (d.b.). A laboratory fluidized bed dryer was utilized in this research. Air temperature levels of 45, 55, 65 and 75°C were applied in drying experiments. Effective moisture diffusivity (D_{eff}) of cantaloupe seeds was computed by Fick's second law in diffusion. Activation energy and specific energy consumption of cantaloupe seeds under different drying conditions were calculated.
Results. Calculated values of D_{eff} for drying experiments were in the range of $2.23 \cdot 10^{-10}$ and $8.61 \cdot 10^{-10}$ m^2/s. Values of D_{eff} increased as the input air temperature increased. Activation energy values were computed between 39.21 and 37.55 kJ/mol for 45°C to 75°C, respectively. Specific energy consumption for cantaloupe seeds was calculated at the boundary of $1.58 \cdot 10^5$ and $6.18 \cdot 10^5$ kJ/kg.
Conclusion. Results indicated that applying the fluidized bed condition is more effective for convective drying of cantaloupe seeds. Increasing air velocity tends to decrease in activation energy. Decreasing in drying air temperature in different bed conditions caused increase in the energy value. The aforesaid drying parameters are necessary to optimize the operational condition of fluidized bed dryer and to perfect design of the system.

Key words: fluidized bed drying, moisture diffusivity, cantaloupe seeds, thin layer drying, energy

INTRODUCTION

Cantaloupe (*Cucumis melo* L.) is a rich source of vitamins A, B, C and carbohydrate. It can be consumed as fresh and dried form. Total production of cantaloupe in the world is $27 \cdot 10^6$ t per year. Soil and climatic conditions in Iran are suitable for cantaloupe production. Cantaloupe is cultivated on $8 \cdot 10^4$ ha with annual production of $127 \cdot 10^4$ t [FAOSTAT 2009]. One of the main purposes of cultivation of cantaloupe fruit in Iran is utilization of seed both as un-husked and salted seeds as a nibbling snack and also can be used as a source of high quality oil, therefore cantaloupes have many benefits for human health [Seyedabadi et al. 2011, Vouldoukis et al. 2004].

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Knowledge about drying properties of cantaloupe seeds is necessary for designing and optimizing the dryer systems. Among these properties, specific energy consumption, effective moisture diffusivity and activation energy are the most important parameters [Amiri et al. 2011, Hashemi et al. 2009]. In a prevailing part of the year, fresh fruit is not available, so consumers prefer to utilize dried seed with uniform moisture content and suitable colour. Applying a proper drying method of the seeds can reduce drying time, energy consumption and production costs, and also provides the best quality of product [Aghbashlo et al. 2008, Chayjan et al. 2011].

Cantaloupe seeds due to high initial water content are disposed to microbial spoilage. Therefore drying is an essential process in order to increase their storage life. Cantaloupe seed drying is useful due to longer shelf-life, smaller space for storage, storability under ambient temperatures and lighter weight [Doymaz 2004].

Floating of grain bed in air flow is defined as fluidization. Increasing in air flow four conditions of fixed bed, semi fluidized bed (minimum fluidized bed), bubbling fluidized bed and transporting will be developed in a bed of material, respectively. Fluidization is from minimum fluidized bed to transportation point [Kunii and Levenspiel 1991]. One of the most important benefits of fluidized bed drying is high value of heat and mass transfer between material and drying air. Moisture and temperature distribution in the drying material is almost uniform. Fluidized bed drying has been used for drying of agricultural and food materials with high initial moisture content such as: corn [Soponronnarit et al. 1997], green beans [Souraki and Mowla 2007], broad beans [Hashemi et al. 2009], rough rice [Amiri Chayjan et al. 2009] and milky mushroom [Arumuganathan et al. 2009].

Three important criteria in convective drying process are: effective moisture diffusivity (D_{eff}), activation energy (E_a) and specific energy consumption; (*SEC*). D_{eff} is an index of mass transfer in drying process [Sacilik 2007]. E_a is minimum required energy for beginning the drying process [Babalis and Belessiotis 2004, Chayjan et al. 2012]. *SEC* is the consumed energy for eliminating of 1 kg water from cantaloupe seed. Air temperature and velocity affect the aforesaid parameters [Koyuncu et al. 2007].

Although numerous research has been performed about drying properties of different agricultural and food products, nevertheless no study has been accomplished about drying of cantaloupe seed in fixed and fluidized bed conditions. Additionally, drying indices of cantaloupe seed under these states are not available.

The main goals of this research were: 1) to compute the effective moisture diffusivity, activation energy and specific energy consumption of cantaloupe seed during the drying conditions and 2) to find relationship between drying indices and input parameters such as air temperature and bed condition.

MATERIAL AND METHODS

A laboratory fluidized bed was used to carry out the experiments. It included a centrifugal fan with one phase electrical motor and 0.375 kW. An air heating unit was installed behind fan with six electrical heating elements (2 kW). Drying chamber is drum type with 150 mm and 320 mm for diameter and height, respectively. A digital thermostat with ±0.1°C accuracy (Atbin mega, made in Iran) was used to control the inlet air temperature. An inverter with ±0.1 Hz accuracy (Vincker VSD2, made in Taiwan) utilized to control the input air velocity. A thermometer with accuracy of ±0.1°C (Lutron TM-903, made in Taiwan) with type k thermocouple sensor and a hygrometer with accuracy of ±3% RH (Lutron TM-903, made in Taiwan) were used to measure the temperature and air relative humidity, respectively. A measuring device of Standard ST-8897 (made in China) was used to measure and record of the pressure drop and air velocity. It is included a vane type digital anemometer with ±0.1 m/s accuracy and a differential digital manometer with ±0.1 Pa accuracy.

To determine the drying conditions, fluidization characteristic curve (air flow velocity against pressure drop) was plotted first. Air velocity against maximum pressure drop was determined and considered as minimum fluidized bed condition. Minimum fluidized bed, as well as two other points in fixed and fluidized bed domain was selected as experimental conditions.

Fresh cantaloupe seeds were cumulated after cutting several cantaloupe fruits. The seeds were separated from the interior pulp. The clean seed was stored in a refrigerator at 4 ±1°C. The laboratory air relative humidity and temperature during drying varied between 19 to 33% and 22 to 31°C, respectively. Air temperatures of 45, 55, 65, and 75°C were applied in the experiments. Moreover, with respect to three bed conditions (air velocity), 12 experiments were totally conducted. Weight of samples was recorded by a digital balance (AND GF-6000, made in Japan) with ±0.01 g accuracy during the experiments. Initial moisture contents of the cantaloupe seeds was determined using gravimetric method at 70°C for 24 h [AOAC 2002]. Initial and final moisture contents of cantaloupe seeds were about 61.99% (d.b.) and 9% (d.b.), respectively.

Moisture ratio during thin-layer drying of cantaloupe seeds was calculated as follows:

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

where MR is the moisture ratio, M is the moisture content at time t (% d.b.), M_0 and M_e are the initial and equilibrium moisture contents, respectively (% d.b.).

During drying of cantaloupe seeds in the fixed and fluidized bed dryer, M_e was relatively negligible compared to M and M_0. Thus the equation (1) can be simplified as follow [Doymaz 2004, Pala et al. 1996]:

$$MR = \frac{M}{M_0} \tag{2}$$

Effective moisture diffusivity of cantaloupe seeds calculated as follows:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(\frac{-D_{\text{eff}} (2n-1)^2 \pi^2 t}{4L^2} \right) \tag{3}$$

where n = 1, 2, 3, ... is the number of terms in Fick's equation, t is drying time (s), D_{eff} is effective moisture diffusivity (m^2/s) and L is average thickness of cantaloupe seeds (m). The first term of equation (3) was considered for a long drying period [Kingsly 2007]. Thus the equation (3) simplified as follow:

$$MR = \left(\frac{8}{\pi^2} \right) \exp\left(\frac{\pi^2 D_{\text{eff}} t}{4L^2} \right) \tag{4}$$

Linear form of equation (4) is as follow:

$$\ln(MR) = \ln\left(\frac{M - M_e}{M_0 - M_e} \right) = \ln\left(\frac{8}{\pi^2} \right) - \left(\frac{D_{\text{eff}} \pi^2 t}{4L^2} \right) \tag{5}$$

Activation energy can be computed using the following equation (6):

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT} \right) \tag{6}$$

After linearization the equation (9), E_a can be determined as follows:

$$\ln(D_{\text{eff}}) = \ln(D_0) - \left(\frac{E_a}{R} \right)\left(\frac{1}{T} \right) \tag{7}$$

where E_a is activation energy (kJ/mol), R is universal gas constant (8.3143 kJ/mol·K), T is absolute air temperature (K), D_0 is pre-exponential factor of the equation (m^2/s).

Values of $\ln(D_{\text{eff}})$ against $1/T$ were plotted according to equation (10). Three models were fitted to straight lines.

Specific energy consumption (SEC) for cantaloupe seed drying was calculated using the following equation [Zhang et al. 2002]:

$$SEC = (C_{\text{Pa}} + C_{\text{Pv}} h_a) Q t \frac{(T_{\text{in}} - T_{\text{am}})}{m_v V_h} \tag{8}$$

where SEC is specific energy consumption (kJ/kg), C_{Pv} and C_{Pa} are specific heat capacity of vapor and air, respectively, (1004.16 and 1828.8 J/kg °C), Q is the inlet air to drying chamber (m^3/s), t is the total drying time (min), h_a is absolute air humidity (kg$_{\text{vapor}}$/kg$_{\text{dry air}}$), T_{am} and T_{in} are ambient and inlet air temperatures to drying chamber, respectively, (°C), m_v is mass of removal water (kg) and V_h is specific air volume (m^3/kg).

RESULTS AND DISCUSSION

Fluidization curve. Input air velocity at semi fluidized bed was 2.4 m/s. Two other points with air velocities of 1.06 and 4.02 m/s were selected in fixed and fluidized bed domain respectively (Fig. 1). The pressure drop of cantaloupe seed bed for fixed, semi fluidized and fluidized bed conditions (points of A, B and C) were 0.01, 0.05 and 0.04 kPa, respectively. Pressure drop value in semi fluidized bed (point B in Figure 1) was the minimum.

Effective moisture diffusivity. It can be observed from Figure 2 that the input air temperature has an important role in drying time of cantaloupe seeds. An increase in input air temperature caused a significant decrease in drying time. Increase in input air temperature causes increase in energy consumption. Thus the

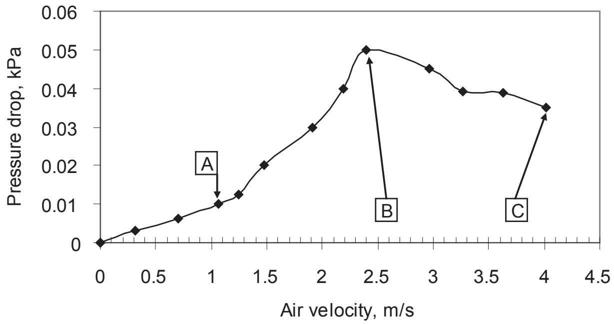

Fig. 1. Fluidization curve of cantaloupe seeds and selected points for modelling: A – fixed bed (1.06 m/s), B – semi fluidized bed (2.4 m/s), C – fluidized bed (4.02 m/s)

drying rate of cantaloupe seed increases. These results are similar to the previous studies, such as: broad bean [Hashemi et al. 2009] and mushroom [Arumuganathan et al. 2009] and canola [Gazor and Mohsenimanesh 2010]. Drying time (hour) against ln(MR) were plotted for all drying conditions (Fig. 3). These results indicated that the drying process of cantaloupe seeds is performed mostly as liquid diffusion. Due to the small thickness of cantaloupe seeds (about 2.47 mm), one falling rate period was occurred. With increasing in temperature level the slope of these curves was proportionally increased. Bed condition has not got a significant effect on slope of D_{eff}. Equation (5) was used

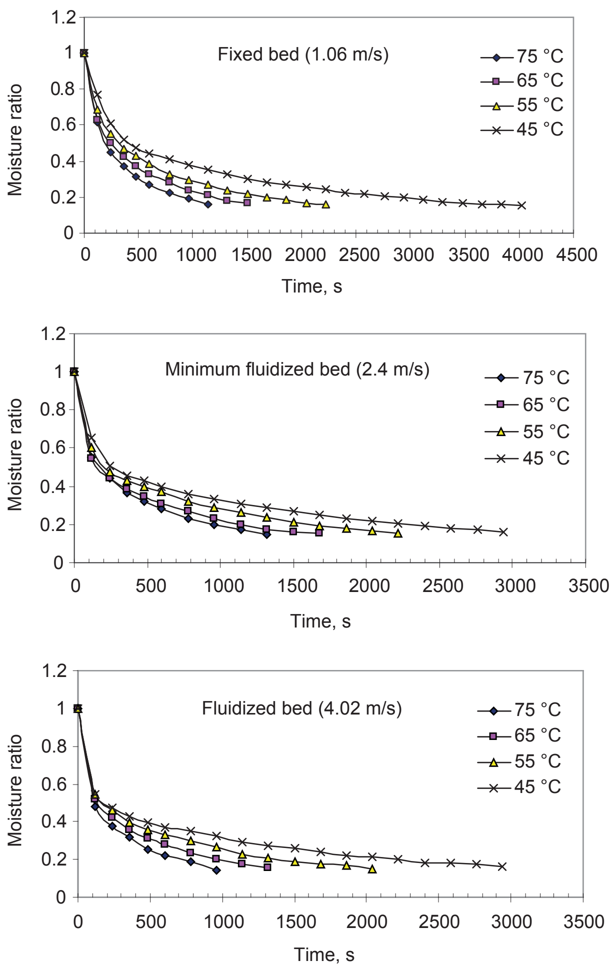

Fig. 2. Moisture ratio of cantaloupe seeds under different drying conditions

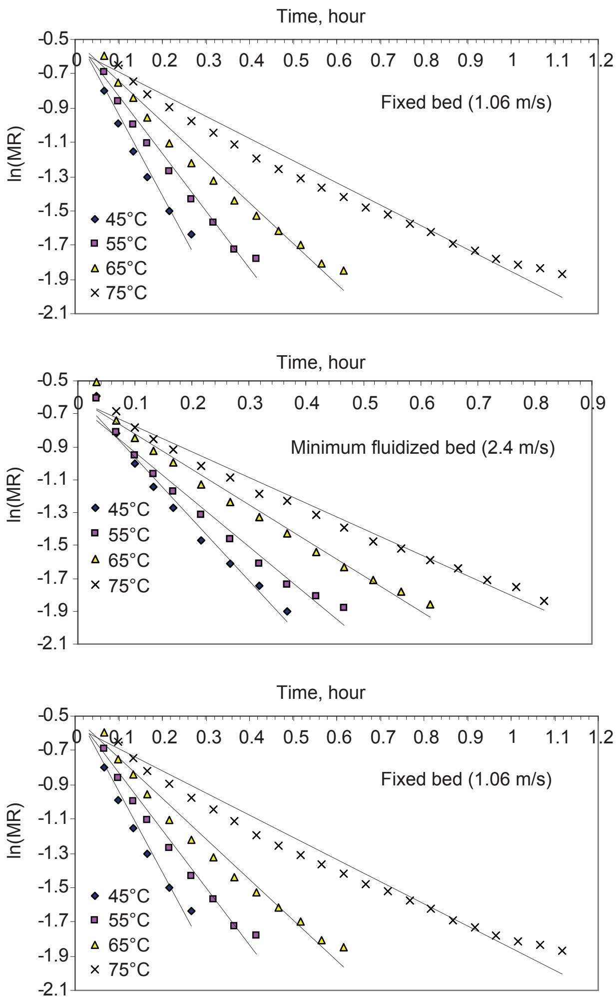

Fig. 3. ln(MR) versus drying time (hour) for thin-layer semi fluidized and fluidized bed drying of cantaloupe seeds

Table 1. Effective moisture diffusivity of cantaloupe seeds for different drying conditions

Temperature °C	Fixed bed (v = 1.06 m/s)		Semi fluidized bed (v = 2.4 m/s)		Fluidized bed (v = 4.02 m/s)	
	D_{eff}, m²/s	R^2	D_{eff}, m²/s	R^2	D_{eff}, m²/s	R^2
45	$2.23 \cdot 10^{-10}$	0.9505	$2.47 \cdot 10^{-10}$	0.9667	$2.50 \cdot 10^{-10}$	0.9773
55	$4.07 \cdot 10^{-10}$	0.9664	$4.04 \cdot 10^{-10}$	0.9782	$4.24 \cdot 10^{-10}$	0.9755
65	$5.80 \cdot 10^{-10}$	0.9749	$5.96 \cdot 10^{-10}$	0.9751	$6.08 \cdot 10^{-10}$	0.9849
75	$8.17 \cdot 10^{-10}$	0.9640	$8.46 \cdot 10^{-10}$	0.9788	$8.61 \cdot 10^{-10}$	0.9855

to calculate the D_{eff} (Table 1). Minimum and maximum values of D_{eff} were found to be $2.23 \cdot 10^{-10}$ m²/s and $8.61 \cdot 10^{-10}$ m²/s, respectively. Maximum values belonged to air temperature of 80°C and fluidized bed (4.02 m/s) condition. Also, minimum value belonged to fixed bed (1.06 m/s) condition with air temperature of 45°C. These results showed that the higher temperature is better to dry the cantaloupe seed in the selected experimental domain, because the obtained values of D_{eff} are relatively higher. Also air temperature was the most important factor which affected the D_{eff} of cantaloupe seeds. Similar result has been reported in drying of peaches [Kingsly et al. 2007] and plums [Goyal et al. 2007].

Figure 4 shows the calculated D_{eff} versus air temperature at different bed conditions. A linear model was applied to fit on D_{eff} values of different bed conditions as follows:

$$D_{eff} = (2 \cdot 10^{-11}\, T) - (9 \cdot 10^{-12}\, v) - (7 \cdot 10^{-10}) \quad R^2 = 0.9940 \quad (9)$$

Related R^2 values showed that these models have adequate precision to model D_{eff} based on air temperature. Results proved that fluidized bed condition (high air velocity) has not got a significant effect on mass transfer of cantaloupe seeds.

Activation energy. ln(D_{eff}) of cantaloupe seeds was plotted against $1/T_a$ (Fig. 5). Curve slopes were used to compute the activation energy (E_a). The E_a of cantaloupe seeds in all bed conditions and related R^2 values are presented in Table 2. E_a of different agricultural and food products was placed between 12 to 110 kJ/mol [Aghbashlo et al. 2008].

According to the results, E_a of cantaloupe seeds varied between 37.55 and 39.21 kJ/mol for fluidized and fixed bed conditions, respectively. Several forms of water in agricultural and food materials included

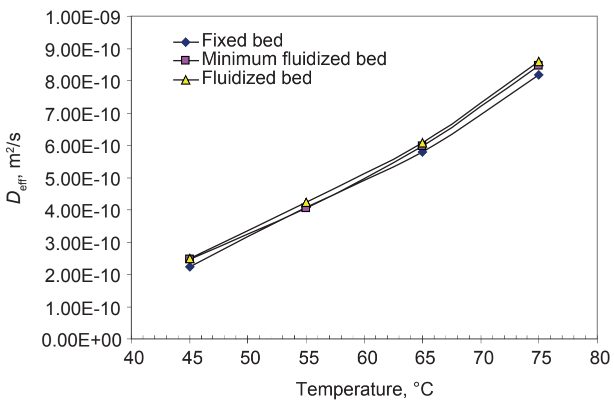

Fig. 4. Influence of air temperature and bed condition on D_{eff} of cantaloupe seeds in thin-layer drying

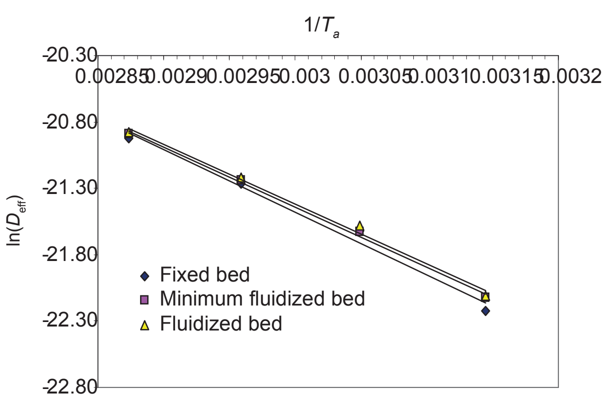

Fig. 5. ln(D_{eff}) against 1/T at different bed conditions for thin-layer drying of cantaloupe seeds

Table 2. Activation energy of cantaloupe seeds and related R^2 values for different beds conditions

Bed condition	Fixed bed (v = 1.06 m/s)	Semi fluidized bed (v = 2.4 m/s)	Fluidized bed (v = 4.02 m/s)
E_a, kJ/mol	39.21	37.63	37.55
R^2	0.9855	0.9971	0.9934
Equation	$\ln(D_{\text{eff}}) = -7.33 - \frac{4716.5}{T}$	$\ln(D_{\text{eff}}) = -7.86 - \frac{4525.8}{T}$	$\ln(D_{\text{eff}}) = -7.87 - \frac{4515.9}{T}$

surfacefree and bound water. Probably most of the water in cantaloupe seed is bound. Accordingly, drying process was conducted as falling rate [Doymaz 2007]. This phenomenon is an increasing agent of energy consumption in cantaloupe seed drying process. In addition, this condition caused decreases of the effect of temperature and air velocity on moisture transfer. In this stage, increase in air temperature exerts injuries in physical and chemical properties [Amiri Chayjan et al. 2009]. Due to the external coat, internal structure, and composition of cantaloupe seed, drying rate occurred in falling rate period and the E_a value is relatively high.

Figure 6 shows E_a values of cantaloupe seed in each bed condition. A two order polynomial model was fitted to the E_a data set as follows:

$$E_a = 3.006v^2 - 7.680v + 42.303 \qquad R^2 = 1 \qquad (10)$$

R^2 showed that a good correlation has been established between E_a and air velocity. Maximum value of E_a (39.21 kJ/mol) obtained at fixed bed condition with air velocity of 1.06 m/s (Fig. 6). Also increase in air velocity, has caused a decrease in activation energy. Similar trend has been found by Aghbashlo et al. [2008] for berberies fruit.

Energy consumption. Specific energy consumption (*SEC*) of cantaloupe seeds was computed using equation (11). This energy is required to eliminate 1 kg water from fresh cantaloupe seeds in hot air drying. Values of *SEC* for cantaloupe seed drying under different drying conditions have been shown in Figure 7. Increasing in air temperature caused decrease in *SEC* values. Also increasing in air velocity caused an intensive increase in *SEC* value. Minimum *SEC* ($1.58 \cdot 10^5$ kJ/kg) was computed for fixed bed condition and input air temperatures of 70°C. Maximum *SEC* ($6.18 \cdot 10^5$ kJ/kg) was obtained for fluidized bed condition (air velocity of 4.02 m/s) and input air temperature of 50°C. Results emphasized that applying of higher temperature and fluidized bed condition caused an intensive increase in energy consumption compared to the other

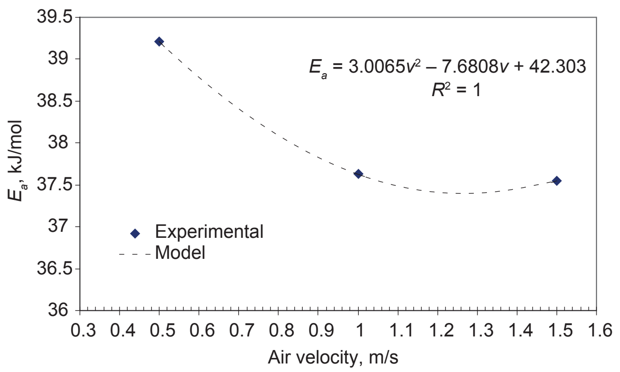

Fig. 6. Influence of bed condition on activation energy of cantaloupe seeds

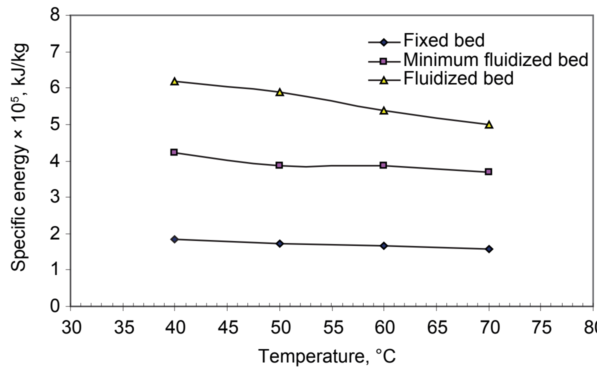

Fig. 7. Effect of drying conditions on specific energy consumption of cantaloupe seeds in thin layer drying

conditions. Accordingly, low temperature level with high air velocity caused a relative decrease in moisture diffusivity, leading to higher *SEC* values. Increase in air velocity has not got any significant effect on moisture diffusivity of cantaloupe seeds, but energy loss was increased. Similar results have been reported in drying of paddy by Khoshtaghaza et al. [2007] and berberies fruit by Aghbashlo et al. [2008] and corn by Chayjan et al. [2011]. *SEC* values using multiple regression analyses is plotted versus temperature and velocity in applied bed conditions. Fitted equation and related R^2 are as follows:

$$SEC = 427.8T - 122655.8v - 71180.1 \quad R^2 = 0.9430 \quad (11)$$

CONCLUSIONS

Results of cantaloupe seeds drying in fixed, semi fluidized and fluidized bed conditions showed that the effective moisture diffusivity for cantaloupe seeds drying varied between $2.23 \cdot 10^{-10}$ and $8.61 \cdot 10^{-10}$ m²/s. Increase in air temperature caused a relatively intensive increase in D_{eff} value for each bed condition, while changing bed condition in each air temperature level did not have significant effect on D_{eff}. Activation energy of cantaloupe seeds varied between 37.55 and 39.21 kJ/mol. Specific energy consumption for thin layer drying of cantaloupe seeds computed between $1.58 \cdot 10^5$ and $6.18 \cdot 10^5$ kJ/kg.

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