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 \( D_{	ext{eff}} \) 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 \( D_{	ext{eff}} \) for drying experiments were in the range of \( 2.23 \times 10^{-10} \) and \( 8.61 \times 10^{-10} \) m²/s. Values of \( D_{	ext{eff}} \) 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 \times 10^5 and 6.18 \times 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 \( 2.7 \times 10^8 \) t per year. Soil and climatic conditions in Iran are suitable for cantaloupe production. Cantaloupe is cultivated on \( 8 \times 10^4 \) ha with annual production of \( 127 \times 10^4 \) 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].
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 ($D_{et}$), activation energy ($E_a$) and specific energy consumption; ($SEC$). $D_{et}$ is an index of mass transfer in drying process [Sacilik 2007]. $E_a$ is minimum required energy for beginning the drying process [Babalis and Beleissiotis 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:

\[ MR = \frac{M - M_e}{M_0 - M_e} \]  
(1)

where \( MR \) is the moisture ratio, \( M \) is the moisture content at time \( t \) (% d.b.), \( M_e \) and \( M_0 \) 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]:

\[ MR = \frac{M}{M_0} \]  
(2)

Effective moisture diffusivity of cantaloupe seeds calculated as follows:

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

where \( n = 1, 2, 3, \ldots \) is the number of terms in Fick’s equation, \( t \) is drying time (s), \( D_{eff} \) is effective moisture diffusivity (m²/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:

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

Linear form of equation (4) is as follow:

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

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

\[ D_{eff} = D_0 \exp \left( - \frac{E_a}{RT} \right) \]  
(6)

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

\[ \ln(D_{eff}) = \ln(D_0) - \left( \frac{E_a}{R} \right) \frac{1}{T} \]  
(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 (m²/s).

Values of \( \ln(D_{eff}) \) 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]:

\[ SEC = (C_{pa} + C_{pu} h_a) Q (T_{in} - T_{am}) \frac{m V_h}{m V_h} \]  
(8)

where SEC is specific energy consumption (kJ/kg), \( C_{pa} \) and \( C_{pu} \) 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 (m³/s), \( t \) is the total drying time (min), \( h_a \) is absolute air humidity (kg_vap/kg_i air), \( T_{am} \) and \( T_{in} \) are ambient and inlet air temperatures to drying chamber, respectively, (°C), \( m \) is mass of removal water (kg) and \( V_h \) is specific air volume (m³/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
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 Mohsenimoghaddam 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

\[ \ln(MR) = \frac{T}{D_{eff}} \]

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)

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
to calculate the $D_{\text{eff}}$ (Table 1). Minimum and maximum values of $D_{\text{eff}}$ were found to be $2.23 \times 10^{-10}$ m$^2$/s and $8.61 \times 10^{-10}$ m$^2$/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 $D_{\text{eff}}$ are relatively higher. Also air temperature was the most important factor which affected the $D_{\text{eff}}$ 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 $D_{\text{eff}}$ versus air temperature at different bed conditions. A linear model was applied to fit on $D_{\text{eff}}$ values of different bed conditions as follows:

$$D_{\text{eff}} = (2 \times 10^{-11} T) - (9 \times 10^{-12} v) - (7 \times 10^{-10})$$

$R^2 = 0.9940$ (9)

Related $R^2$ values showed that these models have adequate precision to model $D_{\text{eff}}$ 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.** $\ln(D_{\text{eff}})$ of cantaloupe seeds was plotted against $1/T$ (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

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

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Fixed bed ($v = 1.06$ m/s)</th>
<th>Semi fluidized bed ($v = 2.4$ m/s)</th>
<th>Fluidized bed ($v = 4.02$ m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_{\text{eff}}$, m$^2$/s</td>
<td>$R^2$</td>
<td>$D_{\text{eff}}$, m$^2$/s</td>
</tr>
<tr>
<td>45</td>
<td>$2.23 \times 10^{-10}$</td>
<td>0.9505</td>
<td>$2.47 \times 10^{-10}$</td>
</tr>
<tr>
<td>55</td>
<td>$4.07 \times 10^{-10}$</td>
<td>0.9664</td>
<td>$4.04 \times 10^{-10}$</td>
</tr>
<tr>
<td>65</td>
<td>$5.80 \times 10^{-10}$</td>
<td>0.9749</td>
<td>$5.96 \times 10^{-10}$</td>
</tr>
<tr>
<td>75</td>
<td>$8.17 \times 10^{-10}$</td>
<td>0.9640</td>
<td>$8.46 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

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

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

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surface free and bound water. Probably most of the water in cantaloupe seed is bound. Accordingly, drying process was conducted as falling rate [Doyman 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:

$$E_a = 3.006v^2 - 7.680v + 42.303 \quad R^2 = 1$$

$R^2$ 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 (1.58·10^5 kJ/kg) was obtained for fixed 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](image1)

![Fig. 7. Effect of drying conditions on specific energy consumption of cantaloupe seeds in thin layer drying](image2)
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 in drying of paddy by Khoshtaghaza et al. [2007] and loss was increased. Similar results have been reported moisture diffusivity of cantaloupe seeds, but energy of cantaloupe seeds varied between 2.23·10^{-10} and 8.61·10^{-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 1.58·10³ and 6.18·10³ kJ/kg.

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 2.23·10^{-10} and 8.61·10^{-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 1.58·10³ and 6.18·10³ kJ/kg.

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