Influence of drying conditions on diffusivity, energy and color of seedless grape after dipping process

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Abstract

Thin layer drying was carried out for Sultana seedless grape after dipping in olive oil and potassium carbonate solution pretreatment. Simulation of raisin production process was performed using experimental data and mathematical models. A laboratory scale convective dryer was used for drying experiments. Second law of Fick was used as a major model to compute the moisture diffusivity with some simplifications. Drying conditions of fixed bed dryer with air temperature levels of 50, 60 and 70 °C and air velocities of 0.25, 0.5, 0.75 and 1 m s\textsuperscript{-1} were applied in this study. Computed values of moisture diffusivity for dried grape varied from a minimum of 7.77E-11 to a maximum of 2.62E-10 m\textsuperscript{2} s\textsuperscript{-1} under drying conditions. Moisture diffusivity values were increased as air temperature was increased. Activation energy values varied from a minimum of 44.806 kJ mol\textsuperscript{-1} to a maximum of 46.302 kJ mol\textsuperscript{-1} in this study. Maximum value of activation energy was obtained at air velocity of 1 m s\textsuperscript{-1}. Lightness value for dried grapes was highest at air velocity of 1 m s\textsuperscript{-1} and 70°C. Color analysis of dried grape proved that the best condition for raisin production process was achieved at air temperature between 60-70°C and air velocity of 1 m s\textsuperscript{-1}. Specific energy consumption values for grape thin layer drying were found to be in the range of 547 and 1904 MJ kg\textsuperscript{-1}. Increase in drying temperature for each air velocity level caused a decrease in specific energy consumption. These grape properties are necessary to determine the best point of drying process and designing the apparatus.

Keywords: energy, grape, moisture diffusivity, thin layer drying

Abbreviations:

- $C_{pv}$ = specific heat capacity of vapor, 1004.16 J kg\textsuperscript{-1} °C\textsuperscript{-1}
- $C_{pa}$ = specific heat capacity of air, 1828.8 J kg\textsuperscript{-1} °C\textsuperscript{-1}
- $D_0$ = pre-exponential factor of the Arrhenius equation, m\textsuperscript{2} s\textsuperscript{-1}
- $D_e$ = effective moisture diffusivity, m\textsuperscript{2} s\textsuperscript{-1}
- $E_a$ = activation energy, kJ mol\textsuperscript{-1}
- $h_u$ = absolute air humidity, kg vapor kg\textsuperscript{-1} dry air
- $m_e$ = mass of removal water, kg
- $M$ = moisture content, kg water kg\textsuperscript{-1} dry matter
- $M_0$ = initial moisture content, kg water kg\textsuperscript{-1} dry matter
- $M_e$ = equilibrium moisture content (%, w.b.)
- $n$ = 1, 2, 3, . . . the number of terms taken into consideration
- $Q$ = inlet air to drying chamber, m\textsuperscript{3} s\textsuperscript{-1}
- $R$ = radius of kernel, m
- $R_0$ = universal gas constant, 8.3143 kJ mol\textsuperscript{-1} K\textsuperscript{-1}
- $SE$ = specific energy consumption kJ kg\textsuperscript{-1}
- $t$ = drying time, s
- $T_a$ = absolute air temperature, K
- $T_{in}$ = inlet air temperature to drying chamber, °C
- $T_{air}$ = ambient air temperatures, °C
- $V_h$ = specific air volume, m\textsuperscript{3} kg\textsuperscript{-1}
Introduction

Grape is one of the most important Iranian horticultural products dried for safe storage over an extended period and known as the best source of carbohydrate, organic compounds and minerals. Dried grapes have a high export value for the country producing 220,000 tones in 2007. Raisin could be preserved for relatively long time using new drying technology. A lot of by-products are produced from grape and raisin. In order to keep the customer’s trust, it is very important to improve grape processing through drying, storing and packaging systems. Drying is the most important stage in grape processing chain. In Iran, harvested grapes are traditionally dipped into olive oil and potassium carbonate solution to remove the waxy layer of skin and dried naturally in the sun. Drying agricultural products through the conventional methods requires great energy because the operation is not quite efficient (Karathanos and Belessiotis, 1999). Optimization of the processing parameters is necessary to increase the efficiency and to reduce the energy consumption. A convenient way to do this is to compute the main parameters of drying system as well as modeling system behavior using simple equations. Some thermal and physical properties of agricultural products such as moisture diffusion, heat and mass transfer, activation energy and specific energy consumption are also important for the proper dryer design (Aghbashlo et al., 2008). Thermal properties, appearance and energy requirement of agricultural products are widely changed under different conditions of convective drying process. These variations are influenced by materials and drying parameters. Grape drying is often carried out using traditional or industrial method with different chemical solutions. The process is called “pretreatment”, and continued by convective drying. As pretreatment always tends to decrease the drying time, this process has been applied to grape by many researchers (Pangavhane et al., 1999; Doyraz and Pala, 2002; Azzouz et al., 2002). Furthermore, several experiments have been carried out for single-layer drying to determine the best model of predicting drying curve for agricultural products such as: hazelnuts (Ozedmir and Devres, 1999), potato slices (Akpinar et al., 2003), candle nuts (Tarigan et al., 2006), onion slices (Pathare and Sharma, 2006), plums (Goyal et al., 2007), beriberi fruit (Aghbashlo et al., 2009) and milky mushroom (Arumuganathan et al., 2009). Moisture diffusivities, activation energy, color and specific energy consumption are important indices used to determine the best process of optimizing heat and mass transfer ability of agricultural crops. These indices which are the crop properties could be changed by pretreatment type. In the other word, these factors specify the physical changes of grape, which occur in the drying operation. For example, effective moisture diffusivity can express the internal porosity and the curvature of the crop. It also states shrinkage, deformation, structure and composition of food and agricultural material, as well as the interactions between material, water and drying period (Zogzas et al., 1996; Achanta and Okos, 1996). Pretreatments have a noticeable effect on the moisture diffusivity of grape. Calculating moisture diffusivity of pretreated grape at a wide range of input drying parameters would be useful in applying proper drying process as well as air velocity and temperature. Among the various dried grape quality indices, color which is defined as the appearance of product is the most important factor, affected by drying conditions and determined marketing value and acceptability of the final product (Doyraz and Pala, 2002). No study has so far been performed on the thermal characteristics, color change and energy consumption of Sultana seedless grapes after dipping in traditional solution of olive oil and potassium carbonate. No information about moisture diffusivity, activation energy, color and specific energy consumption of Sultana seedless grapes is also available. The main goal of this study was to investigate the influence of drying conditions including Iranian traditional pretreatments, air velocity and temperature on the moisture diffusivity, activation energy, color and specific energy consumption of seedless Sultana grapes using a convective drying method and representing the related models for different conditions.

Materials and methods

Experimental Procedure

Sultana seedless grape (Vitis vinifera L.) was supplied from a local grape producer, Hamedan, Iran. Uniform size grape berries with the radius of about 6.64±0.24 mm and initial moisture content of 76.39±1.38% (w.b.) were used. Pretreatment solution used for dipping grape was 2.5% K₂CO₃ + 2% olive oil. Drying process was carried out in an experimental dryer fabricated in Agricultural Machinery Engineering Department of Bu-Ali Sina University, Hamedan, Iran (Fig. 1).

In each experiment, 500 g fresh grape was utilized. During drying process, Weight loss of the samples was measured online at one hour intervals using a digital balance (AND GF-600) connected to a computer through a port of RS-232. Moisture content of the samples was then determined. Air flow rate and color parameters (L "lightness", a "redness" and b "yellowness") were also measured using a Lutron AM-4203 Vane probe anemometer and a Minolta CR 300 colorimeter, respectively.

Grape samples were dipped in potassium carbonate solution for about 60s at ambient temperature (26±2°C) and dried afterward using a laboratory scale thin layer dryer. In this dryer, air flow is perpendicular to the samples. Drying air temperature was adjusted to 50, 60 and 70°C and the air velocity was regulated at 0.25, 0.5, 0.75 and 1 m s⁻¹. Drying process was terminated when the difference of two measured weight became lower than 0.001g. The experiments were repeated three times and the average value of the moisture ratio at each experiment was used to draw the drying curve.

Theoretical Principle

The Fick’s second law of diffusion for a sphere with assumptions of moisture migration in diffusion, negligible volume shrinkage and constant temperature and diffusion coefficients were applied in this study (Dimatteo et al., 2000):

\[ \frac{\partial M}{\partial t} = \nabla \left( D_e \nabla (M) \right) \]

(1)

Where \( M \) is moisture content (% w.b.), \( t \) is drying time (s) and \( D_e \) is effective moisture diffusivity representing the conductive term of all moisture transfer mechanisms (m² s⁻¹). In the case of thin layer drying, with assumptions of 1) one dimensional moisture diffusivity and 2) uniform moisture distribution and negligible external resistance, Eq. (1) can be simplified as follows:

\[ M = M_e + \frac{6}{\pi^2} \left( M_0 - M_e \right) \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -\frac{D_e n^2 \pi^2 t}{R^2} \right) \]

(2)

where \( M_0 \) is initial moisture content (% w.b.), \( M_e \) is equilibrium moisture content (% w.b.), \( n \) is the number of...
Table 1. Effective moisture diffusivity and correlation coefficient for experimental data of dried grape

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>V=0.25 m/s</th>
<th>V=0.5 m/s</th>
<th>V=0.75 m/s</th>
<th>V=1 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_e$</td>
<td>$R^2$</td>
<td>$D_e$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>50</td>
<td>7.77E-11</td>
<td>0.9987</td>
<td>8.30E-11</td>
<td>0.9986</td>
</tr>
<tr>
<td>60</td>
<td>1.43E-10</td>
<td>0.9985</td>
<td>1.56E-10</td>
<td>0.9980</td>
</tr>
<tr>
<td>70</td>
<td>2.12E-10</td>
<td>0.9970</td>
<td>2.19E-10</td>
<td>0.9976</td>
</tr>
</tbody>
</table>

Table 2. Fitted linear models to $D_e$ value in grape drying process at different air velocities

<table>
<thead>
<tr>
<th>Air velocity (m s⁻¹)</th>
<th>Model</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>$D_e$=7E-12T-3E-10</td>
<td>0.9999</td>
</tr>
<tr>
<td>0.5</td>
<td>$D_e$=7E-12T-3E-10</td>
<td>0.9980</td>
</tr>
<tr>
<td>0.75</td>
<td>$D_e$=8E-12T-3E-10</td>
<td>0.9994</td>
</tr>
<tr>
<td>1</td>
<td>$D_e$=8E-12T-3E-10</td>
<td>0.9989</td>
</tr>
</tbody>
</table>

$SE = \left( t \left( \frac{E_D}{m_1} \right) \frac{Q(C_{P_u} + C_{P_v}h_a)}{V_i} \right) (T_{in} - T_{am})$ (10)

Where $SE$ is specific energy consumption (kJ kg⁻¹), $t$ is total drying time (min⁻¹), $m_1$ is mass of removal water (kg), $C_{P_u}$ is specific heat capacity of vapor (1004.16 J kg⁻¹ °C⁻¹), $C_{P_v}$ is specific heat capacity of air (1828.8 J kg⁻¹ °C⁻¹), $Q$ is inlet air to drying chamber (m³ s⁻¹), $V_i$ is specific air volume (m³ kg⁻¹), $h_a$ is absolute air humidity (kgvapor kg⁻¹ dry air). $T_{in}$ is inlet air temperature to drying chamber (°C) and $T_{am}$ is ambient air temperature (°C).

Results and discussion

Effective moisture diffusivity

Variations of moisture ratio in each air velocity and temperature are presented in Fig. 2. Fig. 3 shows the values of $\ln(X)$ against drying time (s) in different levels of air velocity and temperature. These drying curves proved that the grape drying process occurred in falling rate period. In other words, controlling factor in drying process was drying air velocity caused an increase in $D_e$. Values of $D_e$ were computed using Eq. (6). These values are presented in Table 1 for all levels of air velocities and temperatures. The maximum value of $D_e = 2.62E-10$ m² s⁻¹ during the experiments was belonged to the air velocity of 1 m s⁻¹ and the air temperature of 70°C. The minimum value of $D_e = 7.77E-11$ m² s⁻¹ was belonged to air velocity of 0.25 m s⁻¹ and the air temperature of 50°C. Air temperature had greater effect on the $D_e$ values of grape (Fig. 4). It is obvious from the Table 1 and Figure 4 that the $D_e$ value was increased as air temperature increased. A similar effect of air temperature on moisture diffusivity during convective drying has already
Table 3. Fitted power models to $D_e$ value in grape drying process for different air temperatures

<table>
<thead>
<tr>
<th>Air temperature (°C)</th>
<th>Model</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>$D_e = 3E-11V + 7E-11$</td>
<td>0.9765</td>
</tr>
<tr>
<td>60</td>
<td>$D_e = 4E-11V + 1E-10$</td>
<td>0.9893</td>
</tr>
<tr>
<td>70</td>
<td>$D_e = 7E-11V + 2E-10$</td>
<td>0.9594</td>
</tr>
</tbody>
</table>

Table 4. Activation energy and related correlation coefficient for different levels of air velocities in grape drying process

<table>
<thead>
<tr>
<th>Air velocity (m s$^{-1}$)</th>
<th>$E_a$ (kJ mol$^{-1}$)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V=0.25$ m s$^{-1}$</td>
<td>44.95</td>
<td>0.9879</td>
</tr>
<tr>
<td>$V=0.5$ m s$^{-1}$</td>
<td>45.87</td>
<td>0.9756</td>
</tr>
<tr>
<td>$V=0.75$ m s$^{-1}$</td>
<td>44.81</td>
<td>0.9800</td>
</tr>
<tr>
<td>$V=1$ m s$^{-1}$</td>
<td>46.30</td>
<td>0.9926</td>
</tr>
</tbody>
</table>

Fig 1. Schematic diagram of laboratory scale dryer: (1) inverter, (2) fan, (3) drying chamber, (4) balance, (5) sample tray, (6) thermometer, (7) hygrometer, (8) anemometer, (9) computer, (10) heater and (11) temperature controller.

Fig 2. Moisture ratio of grape in various drying conditions.
Fig 3. Ln (MR) against time (hour) for thin-layer drying of grape at different air velocities

![Graph](image1)

Fig 4. Effect of air temperature and velocity on $D_e$ for thin-layer drying of grape

![Graph](image2)

been found in apricots (Doymaz, 2004), peach (Kingsly et al., 2007), berberis fruit (Agbbashlo et al., 2008), mushroom (Arunmuganathan et al., 2009) and carrot slices (Agbbashlo et al., 2009). Values of $D_e$ were plotted against air velocities at different levels of air temperature and air velocities as shown in Fig. 4. Four linear models were fitted the $D_e$ values based on temperature, and three linear models were fitted based on air velocity. Applied models and related $R^2$ values are presented in Tables 2 and 3. Results showed that the minimum value of $D_e$ was obtained at minimum value of air temperature. Results also proved that influence of air velocity at upper air temperatures was higher. Drying Air Contacted with grape berries at 1 m s$^{-1}$ was most effective because of having the highest $D_e$ values. The effect of air velocity level at lower air temperatures was not significant as well.

**Activation energy**

For determining activation energy, at first values of $1/T_a$ were plotted against $\ln(X)$ as shown in Fig. 5 and then activation energy ($E_a$) was calculated using Eq. (6). $E_a$ values for different air velocity levels and related $R^2$ values are presented in Table 4. $E_a$ values for food and agricultural products were commonly located in boundary of 12.7–110 kJ mol$^{-1}$. Babalis and Belessiotis (2004) reported minimum and maximum values of $E_a$ for figs between 30.8 and 48.47 kJ mol$^{-1}$, respectively. The calculated minimum and maximum
values of $E_a$ for grape were 44.806 and 46.302 kJ mol$^{-1}$ respectively. Surface and chemical absorptions are the forms of water in fruits. Water in the tissue of berries, is in the surface absorption, so little energy is needed to evaporate water and unsuitable change in chemical properties are inconsiderable in drying period. If a proper composition of air velocity and temperature as well as suitable dryer system is selected, occurrence of damages should be decreased. Initial moisture content of grape is very high. The form of water and viscose structure of grape as well as intensive changes of $E_a$ value for air temperature levels at each air velocity, are also the main reasons that the activation energy of grape is high, compared to the other food products. Fig. 6 shows the variations of air velocity against $E_a$. A three degree of polynomial model were fitted to data set and values of $R^2$ were represented (Fig. 6). Maximum value of $E_a$=46.302 kJ mol$^{-1}$ was obtained at air velocity of 1 m s$^{-1}$. In air velocity of 0.25 and 0.75 m s$^{-1}$, the activation energy was decreased. This is because of less effective contact between air stream and grape berries. Minimum and maximum values for beriberi fruit have been calculated as 110.837 kJ mol$^{-1}$ and 130.61 kJ mol$^{-1}$, respectively (Aghbashlo et al., 2008). The average value of this parameter for orange skin has obtained as 36.4 kJ mol$^{-1}$ (Garau et al., 2006).

**Color**

Color is one of the most important quality indices of foods and agricultural products. Unsuitable changes in color of agricultural products would make the food having low quality and marketing value. Results showed that drying system had an important effect on the color parameters of dried grape.

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**Fig 6.** Effect of air velocity on activation energy value for thin-layer drying of grape

**Fig 7.** Values of color indices for dried grape under different drying conditions

**Fig 8.** Specific energy consumption for thin-layer drying of grape at different levels of air temperatures and velocities
Conclusions

Consumption of specific energy (SE) for eliminating of 1 kg moisture from grape using the convective dryer were calculated for each experiment using Eq. (10). Calculated values of SE during the experiments are shown in Fig. 8. When air temperature was decreased, the SE values increased. The effect of air velocity on increasing SE value was more than air temperature. Maximum value of SE (1904 MJ kg⁻¹) was calculated at air velocity of 1 m s⁻¹ with drying air temperature of 50°C, while minimum value of SE (547 MJ kg⁻¹) was calculated at air velocity of 0.25 m s⁻¹ with drying air temperature of 70°C. Results showed that increasing in drying temperature in each air velocity level affected SE inversely. In the other words, increasing air temperature caused the drying time be be shorter, thus energy consumption was decreased. With decreasing air velocity, effective contact between air and grape berries was increased and SE therefore decreased. Similar trends have been reported for paddy (Khoshtaghaza et al., 2007) and berberis fruit (Aghbashlo et al., 2008).

Specific energy consumption

Acknowledgements

The authors would like to thank Bu-Ali Sina University for financial support of this study.

References


