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

Reza Amiri Chayjan*[1], Mir Hossein Peyman[2], Mahmood Esna-Ashari[3] and Kamran Salari[1]

[1]Department of Agricultural Machinery, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran
[2]Department of Agricultural Mechanization, Faculty of Agriculture, Guilan University, Rasht, Iran
[3]Department of Horticultural Sciences, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran

***Corresponding author: amirireza@basu.ac.ir**

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^{-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^2 s^{-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^{-1} to a maximum of 46.302 kJ mol^{-1} in this study. Maximum value of activation energy was obtained at air velocity of 1 m s^{-1}. Lightness value for dried grapes was highest at air velocity of 1 m s^{-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^{-1}. Specific energy consumption values for grape thin layer drying were found to be in the range of 547 and 1904 MJ kg^{-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^{-1} $°C^{-1}$
C_{Pa} = specific heat capacity of air, 1828.8 J kg^{-1} $°C^{-1}$
D_0 = pre-exponential factor of the Arrhenius equation, m^2 s^{-1}
D_e = effective moisture diffusivity, m^2 s^{-1}
E_a = activation energy, kJ mol^{-1}
h_a = absolute air humidity, kg_{vapor} $kg^{-1}_{dry\ air}$
m_v = mass of removal water, kg
M = moisture content, $kg_{water}kg^{-1}_{dry\ mater}$
M_0 = initial moisture content, $kg_{water}kg^{-1}_{dry\ mater}$
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^3 s^{-1}
R = radius of kernel, m
R_0 = universal gas constant, 8.3143 kJ mol^{-1} K^{-1}
SE = specific energy consumption kJ kg^{-1}
t = drying time, s
T_a = absolute air temperature, K
T_{in} = inlet air temperature to drying chamber, °C
T_{am} = ambient air temperatures, °C
V_h = specific air volume, m^3 kg^{-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; Doymaz 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 (Doymaz 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% K_2CO_3 + 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):

$$\frac{\partial M}{\partial t} = \nabla (D_e . \nabla (M)) \quad (1)$$

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 ($m^2\ s^{-1}$). 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:

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

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

Temperature (°C)	V=0.25 m/s		V=0.5 m/s		V=0.75 m/s		V=1 m/s	
	D_e	R^2	D_e	R^2	D_e	R^2	D_e	R^2
50	7.77E-11	0.9987	8.30E-11	0.9986	8.90E-11	0.9982	9.90E-11	0.9979
60	1.43E-10	0.9985	1.56E-10	0.9980	1.68E-10	0.9976	1.76E-10	0.9972
70	2.12E-10	0.9970	2.19E-10	0.9976	2.40E-10	0.9977	2.62E-10	0.9976

terms taken into consideration (1, 2, 3, . . .) and R is radius of kernel (m).
Eq. (2) is written in a dimensionless form as follows:

$$X = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-D_e n^2 \pi^2 t}{R^2}\right) \quad (3)$$

where X is moisture ratio.
Eq. (3) can be simplified to first term of series only for longer drying periods:

$$X = \left(\frac{6}{\pi^2}\right)\exp\left(\frac{D_e \pi^2 t}{R^2}\right) \quad (4)$$

With linearization of Eq (3):

$$\ln(X) = \ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{D_e \pi^2 t}{R^2}\right) \quad (5)$$

Values of equilibrium moisture content (M_e) are relatively small compared to M or M_0. Thus $(M - M_e)/(M_0 - M_e)$ is simplified to M / M_0 (Aghbashlo et al., 2008).
Slope (k_0) was computed by plotting $\ln(X)$ against time according to the Eq. (5):

$$k_0 = \frac{D_e \pi^2}{R^2} \quad (6)$$

Activation energy was computed using an Arrhenius type equation (Akpinar and Bicer, 2005):

$$D_e = D_0 \exp\left(-\frac{E_a}{R_0 T_a}\right) \quad (7)$$

For computing E_a, Eq. (7) can be written as follows:

$$\ln(D_e) = \ln(D_0) - \left(\frac{E_a}{R_0}\right)\left(\frac{1}{T_a}\right) \quad (8)$$

where E_a is activation energy (kJ mol^{-1}), R_0 is universal gas constant (8.3143 kJ mol^{-1} K^{-1}), D_0 is pre-exponential factor of the Arrhenius equation (m^2 s^{-1}) and T_a is absolute air temperature (K).
From Eq. (8), plot of $\ln(D_e)$ against 1/T_a gives a straight slope of K_1.

$$K_1 = \frac{E_a}{R} \quad (9)$$

Linear regression analysis method using MS Excel 2003 was used to fit the equation to the experimental data and then related coefficient of determination (R^2) was obtained.
Consumption of specific energy (SE) was calculated using the following equation (Zhang et al., 2002):

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

Air velocity (m s^{-1})	Model	R^2
0.25	D_e =7E-12T-3E-10	0.9999
0.5	D_e =7E-12T-3E-10	0.9980
0.75	D_e =8E-12T-3E-10	0.9994
1	D_e =8E-12T-3E-10	0.9989

$$SE = \left(\frac{t}{m_v}\right)\left[\frac{Q(C_{Pa} + C_{Pv} h_a)}{V_h}\right](T_{in} - T_{am}) \quad (10)$$

Where SE is specific energy consumption (kJ kg^{-1}), t is total drying time (min^{-1}), m_v is mass of removal water (kg), C_{Pv} is specific heat capacity of vapor (1004.16 J kg^{-1} °C^{-1}), C_{Pa} is specific heat capacity of air (1828.8 J kg^{-1} °C^{-1}), Q is inlet air to drying chamber (m^3 s^{-1}), V_h is specific air volume (m^3 kg^{-1}), h_a is absolute air humidity (kg$_{vapor}$ 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 dry wing force of liquid diffusion. Drying curves were similar to a straight line as the falling rate period (Fig. 3). Drying curve patterns showed that the slop of straight lines was increased when the temperature values increased. The effect of air velocity on the slop of D_e was also adverse, thus decreasing 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 m^2 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 m^2 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

Air temperature (°C)	Model	R^2
50	D_e = 3E-11V+7E-11	0.9765
60	D_e = 4E-11V+1E-10	0.9893
70	D_e = 7E-11V+2E-10	0.9594

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

Air velocity (m s^{-1})	V=0.25 m s^{-1}	V=0.5 m s^{-1}	V=0.75 m s^{-1}	V=1 m s^{-1}
E_a (kJ mol^{-1})	44.95	45.87	44.81	46.30
R^2	0.9879	0.9756	0.9800	0.9926

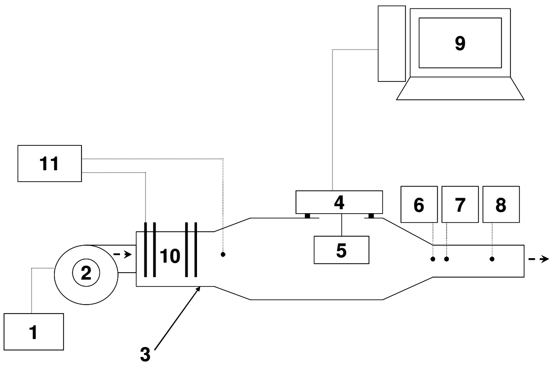

Fig 1. Schematic diagram of laboratory scale dryer: (1) inverter, (2) fan, (3) drying chamber, (4) balance, (5) sample tray, (6) thermometer, (7) hygrometer, (8) anemometer, (9) computer, (10) heater and (11) temperature controller.

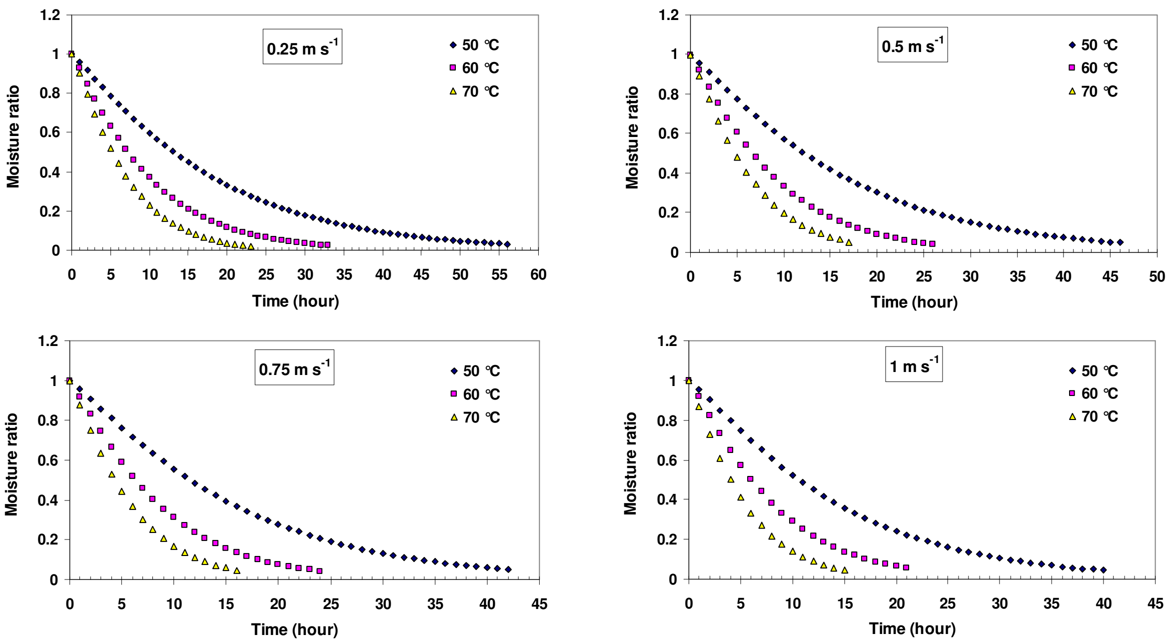

Fig 2. Moisture ratio of grape in various drying conditions

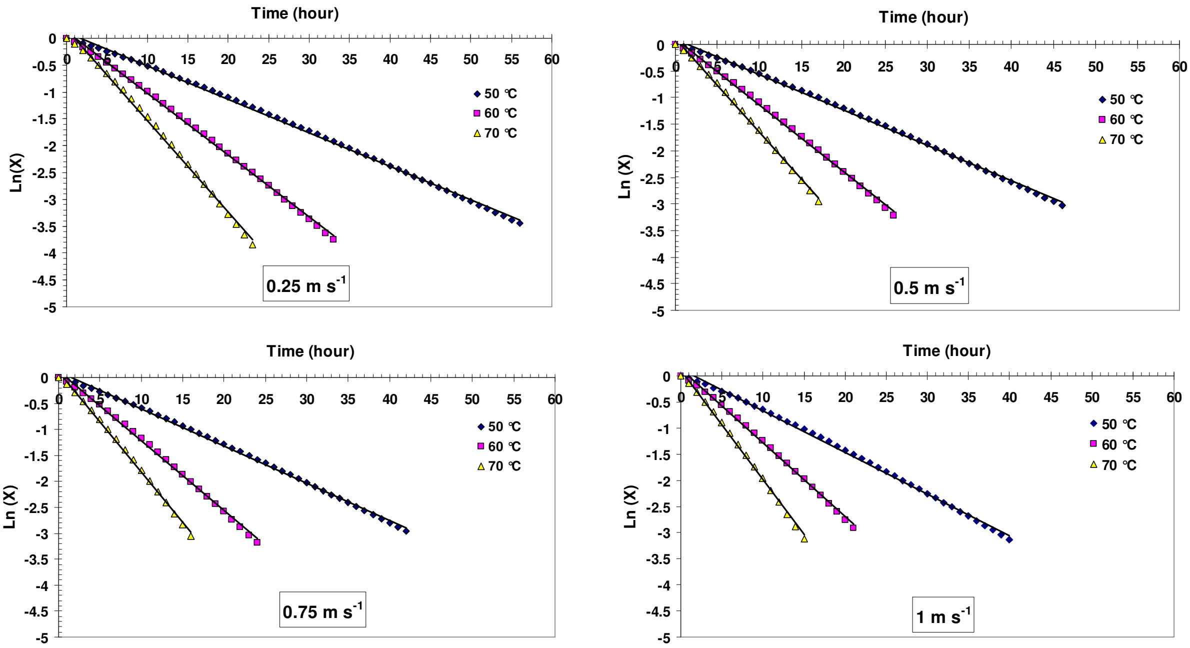

Fig 3. Ln (MR) against time (hour) for thin-layer drying of grape at different air velocities

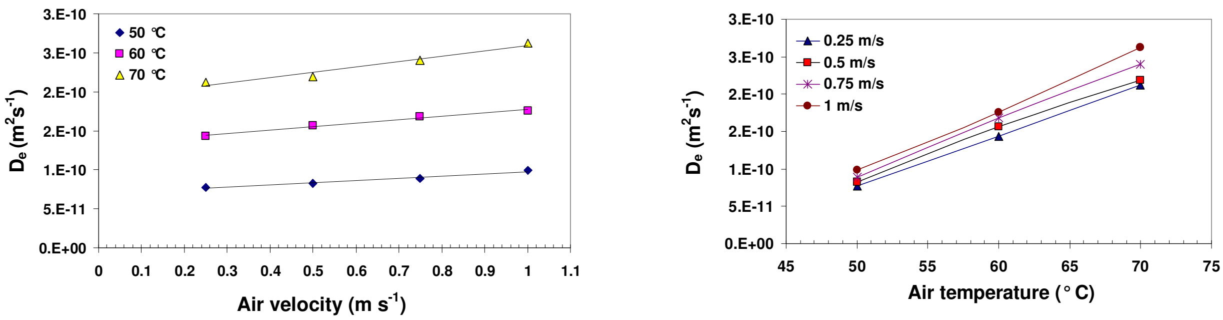

Fig 4. Effect of air temperature and velocity on D_e for thin-layer drying of grape

been found in apricots (Doymaz, 2004), peach (Kingsly et al., 2007), berberis fruit (Aghbashlo et al., 2008), mushroom (Arumuganathan et al., 2009) and carrot slices (Aghbashlo 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 1m 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

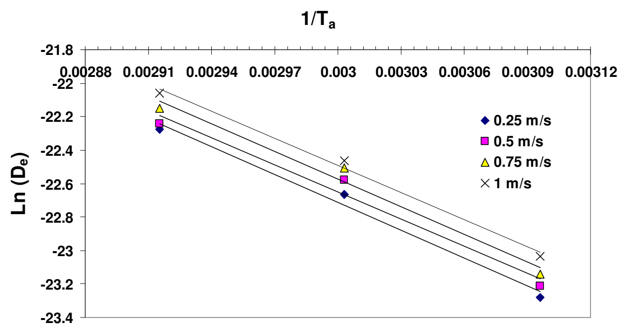

Fig 5. Ln (D_e) against $1/T_a$ at different levels of air velocities for thin-layer drying of grape

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

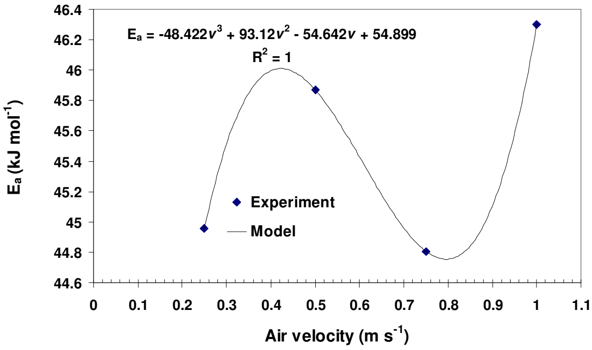

Fig 6. Effect of air velocity on activation energy value for thin-layer drying of grape

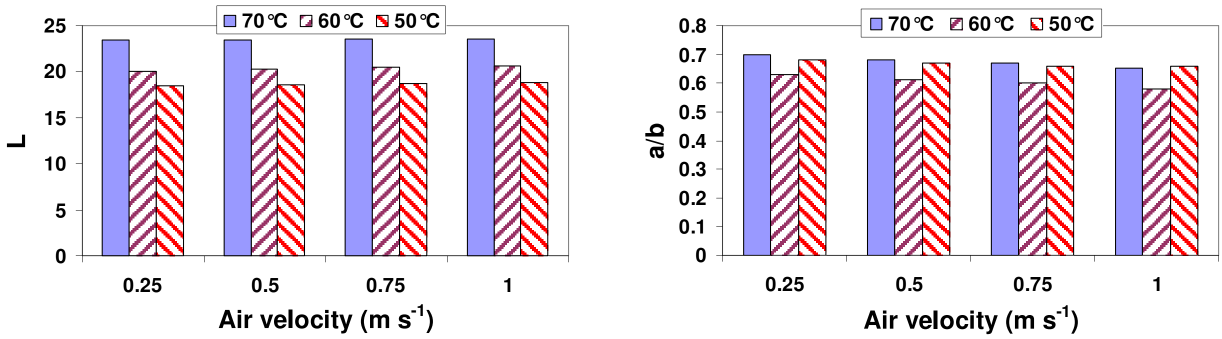

Fig 7. Values of color indices for dried grape under different drying conditions

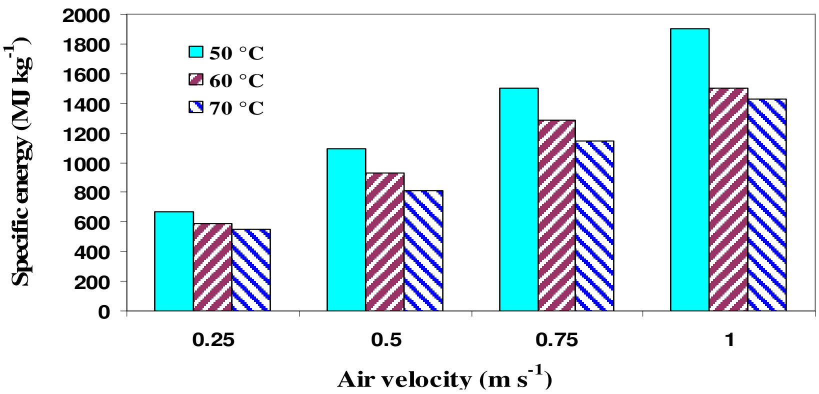

Fig 8. Specific energy consumption for thin-layer drying of grape at different levels of air temperatures and velocities

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 D_e 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

(Fig. 7). Higher value for L and lower value for a/b ratio are desired in food production process. Value of L (lightness) for dried grapes dipped in olive oil and potassium carbonate solution was highest (23.55) at air velocity of 1 m s^{-1} and 70°C. The value of a/b, which is an index of the redness/yellowness color, was minimum at air velocity of 1 m s^{-1} and 60°C. Fig. 7 shows that the values of L were increased with increasing in temperature, whereas the values of a/b for all velocity levels was the best in 60°C. In order to keep the quality (color) of grape, applied temperatures should therefore be between 60 and 70°C.

Specific energy consumption

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).

Conclusions

1- Maximum value of D_e during the experiments was obtained at air velocity of 1 m s^{-1} and the air temperature of 70°C. Minimum value of D_e was obtained at air velocity of 0.25 m s^{-1} and the air temperature of 50°C. Air temperature had greater effect on D_e values of dried grape. D_e values were also increased as air temperature increased.
2- Minimum and maximum values of E_a for dried grape were varied between 44.806 and 46.302 kJ mol^{-1}. Maximum value of E_a was obtained at air velocity of 1 m s^{-1}. At air velocities of 0.25 and 0.75 m s^{-1}, activation energy was decreased.
3- Lightness value for dried grapes was highest at air velocity of 1 m s^{-1} and 70°C. The a/b value was minimum at air velocity of 1 m s^{-1} and 60°C. Value of L was increase with increasing temperature. The a/b values for all velocity levels were the best in 60°C. In order to keep the quality (color) of grape, applied temperature should therefore be between 60 and 70°C.
4- Maximum value of SE was obtained at air velocity of 1 m s^{-1} with drying air temperature of 50°C. Minimum value of SE was obtained at air velocity of 0.25 m s^{-1} with drying air temperature of 70°C. Increasing drying temperature in each air velocity level affected SE inversely. The effect of air velocity on increasing SE was more than air temperature.

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