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Research Article

Analysis of Mass And Heat Transfer Coefficients, Energy Consumption and Efficiency of in Dehydration of Cornelian Cherry

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Keywords

Cornelian cherry, Effective diffusivity, Heat and mass transfer, Energy efficiency, Thermal properties.

Abstract

Drying is the process of removing water or other liquids from materials. However, drying is commonly used to remove water from food by thermal methods. Drying technology is a combination of transport phenomena and material science. Knowing the mass and heat transfer properties and the energy for the drying process is very important in terms of controlling and improving the process. In the present study, the effects of experimental parameters such as the temperature and velocity of air on mass and heat transfer coefficients, consumption and efficiency of energy in the dehydration of cornelian cherry were investigated. The cornelian cherry fruit was dried in a single layer in a dryer as convective at three different values (50, 60 and 70°C) of air temperatures and three different values (0.4, 0.7 and 1.0 m/s) of air velocities. The effective diffusivity values of moisture (D_{eff}), coefficient of mass transfer (k), and Bi number were calculated using Dincer and Dost analytical approach. The heat capacity, thermal diffusivity and thermal conductivity are calculated as a function of moisture content. The convective heat and mass transfer coefficients were determined using engineering correlations and the Chilton-Colburn analogy. The consumption and efficiency of energy, thermal efficiency, and the efficiency of drying were analyzed for all experimental conditions.

1. Introduction

Cornelian cherry (*Cornus mas L.*) naturally grows in southern and central Europe, southwest Asia, China, and Turkey. It can grow from a large shrub to a small tree growing up to about 5-15 m in height [1]. Cornelian cherry fruit has external color yellow, pink and red, is sweet-sour in taste, and is olive-shaped. Since cornelian cherry contains vitamin C, antioxidants, anthocyanins, flavonoids, organic acids, and melatonin, it plays an important role in traditional medicine in many countries of Asia and Europe. It is generally preferred in the treatment of skin diseases, obesity, diarrhea, cholera, ulcers, colitis, diabetes, rheumatism, cough, bronchitis, and cancer. Also, the fruits of cornelian cherry are used to produce such as marmalade, jam, soup, compote, and soft drinks [2].

Drying is often used as a final operation in the manufacturing process such as paper, textiles, coal, soap, fertilizers, dyestuff, etc. before selling or packaging products. Approximately 7-15% of the total energy produced in industrialized countries is consumed in the drying process [3]. Since fresh vegetables and fruits contain high moisture that causes microbial spoilage, keeping them long-term post-harvest is a serious problem. Drying is widely used as a protection method for foodstuffs. The dried materials have a longer shelf-life and, cheaper transport and packaging costs. Although many drying techniques such as freeze, infrared, vacuum, microwave, and their combinations have been developed, the convective drying technique is still widely used in industrial applications. Convective dryers are used in more than 85% of dryers to dry foodstuffs [4]. Knowing the transfer properties of mass and heat and energy consumption during drying is very important in terms of controlling and improving the process.

In a convective dryer, the removal of water from the moist material is accomplished by the simultaneous use of transfer of mass, heat, and momentum. In the drying process, the transfer of mass and heat takes place simultaneously in an unsteady state. Heat is transferred by convection to the material surface to be dried through heated air and then heat is transferred from the material surface to the inside with conduction. The solid material temperature and the water inside the solid material increase, and moisture in the material evaporates. Evaporated moisture is transferred to the solid surface through diffusion, and then it is convectively transferred from the solid-air interface to the air. In drying, water remains under the influence of external and internal resistors until it passes from inside the fruit to the environment outside the fruit. While internal resistors are related to the structure, content, thickness, and water content of the solid, external resistances are related to the boundary layer thickness that occurs according to the thermophysical property and velocity of air in drying. Depending on the circumstances, only one of these resistances can be dominant or both can be effective [5, 6].

The drying of cornelian cherry in different dryers and drying conditions has been investigated by many researchers. Some of these researches have focused on the effect of different methods of drying and conditions on physicochemical properties [7, 8], bioactive substances [9], and quality parameters [10] of cornelian cherry. Also, the effects of conditions of drying such as velocity and temperature of the air on drying time, total energy requirement [11, 12], and drying kinetics of cornelian cherry [13] have been analyzed. A literature survey has shown that any data on moisture diffusivity, thermal diffusivity, convective mass, heat transfer coefficients, and thermodynamic properties of cornelian cherry has not been yet reported.

The purpose of the present study determined transport properties such as effective diffusivity of moisture, Biot number, thermal diffusivity, coefficient of mass and heat transfer of convective dried cornelian cherry fruit, to calculate the consumption and efficiency of energy.

2. Materials and methods

2.1. Material

Cornelian cherry fruits were provided in Erzurum, Turkey. The fruits with full red color were selected by usual. Fruits were separated from the peduncle, washed to remove impurities on the surface in tap water, and then wiped with towel paper. To determine the first moisture content of cornelian cherry, a portion of the fresh fruit was dried at atmospheric pressure in an oven and 105±2°C at 24 for hours [14]. Cornelian cherry fruit consists of two parts: pulp and stone. Since the fruits were dried as a whole, the shares of total moisture in pulp and stone were investigated. Pulp and stone were separated. Both pulp and stone were dried at 105±5°C for 24 h. The average first moisture

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content of fresh fruit was found as about 3.065 g water /g dry matter. It was determined that about 5% of the total moisture was in the stone and 95% was in the pulp. The fresh fruits were placed into 100-gram portions in plastic bags and stored in a refrigerator at +4°C (Arçelik 2536, Turkey) to protect them, till used in drying experiments.

2.2. Experimental design

The experiments for the drying process were performed using a laboratory-type convective drier (0.30x0.28x2.50 m) The general shape of the dryer is given in Figure 1. The velocity (0.4, 0,7 and 1.0 m/s) and temperature (50, 60 and 70°C) of air were selected as the experimental parameter.

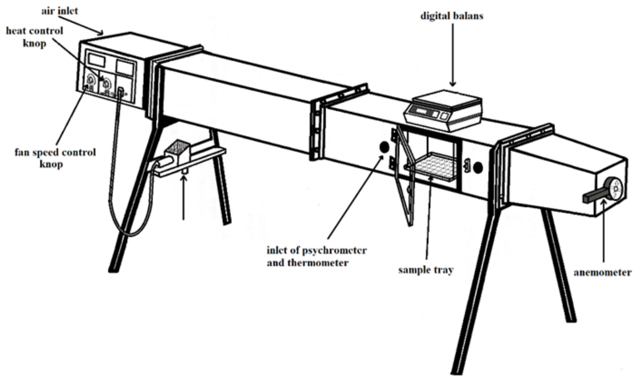

Figure 1. Tunnel-type convective dryer

The dryer was set to the desired experiment conditions and was worked empty for half an hour to achieve a steady-state condition. Then, the fruits (about 100 g) were distributed on the tray as a single layer, and weight loss was periodically recorded for one-hour periods during the drying processes with a precision balance. To measure the air velocity was used an anemometer (HALT-08). When moisture content decreased from 3.065±0.03 to 0.09±0.01 on a dry basis, experiments were completed. Ambient air had a temperature of 21±2°C and relative humidity of 0.005±0.001(g water/g dry air). All of the experiment was repeated two times and the data were the average of these experiments.

2.3. Theoretical approaches

2.3.1. Determination of mass transfer coefficients

To explain the transport of water from the food in an unsteady state was be used Fick's second law.

$$\frac{\partial \mu}{\partial t} = D_{eff}\nabla^2 M \quad (1)$$

To calculate the coefficients of mass transfer for geometrically and irregularly shaped material was developed and verified analytically a solution by Dincer and Dost. They have solved Eq.1 to determine the mass transfer coefficients for a solid sphere using the following assumptions and boundary conditions [15].

- ✓ The thermophysical properties of the fluid and the solid have constant.
- ✓ The effect of mass and heat transfer is neglected.
- ✓ The moisture diffusion in a solid sphere only happens in the radial direction.

$$t = 0 \quad M_{(r,0)} = M_r = \text{constant}$$

$$r = 0 \quad \left(\frac{\partial M_{(r,0)}}{\partial r}\right) = 0$$

$$r = R \quad -D_{eff}\left(\frac{\partial M_{(R,t)}}{\partial r}\right) = h_m\left(M_{(R,t)} - M_{(e)}\right) \quad (2)$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} A_n B_n \quad \text{for } 0.1 < Bi$$

The Fourier number (F_o > 0.2) in Eq. (2) can be simplified for negligibly small values. Thus, only the first term in Eq. (2) is well approximated [16].

$$MR \cong A_1 B_1 \quad (3)$$

For a spherical object;

$$A_1 = G = \exp[0.7599.\,Bi/(2.1 + Bi)] \quad (4)$$

$$B_1 = \exp(-\mu_1^2 F_0) \quad (5)$$

F_o is a Fourier number which is shown as follows:

$$F_0 = \frac{D_{eff}}{R^2} t \quad (6)$$

The dimensionless moisture distribution is defined in the following exponential form [15];

$$MR = G\exp(-St)F_0 = \frac{D_{eff}}{R^2} t \quad (7)$$

The Biot Number *(Bi)* for a spherical object is defined as Eq. (8):

$$Bi = \frac{2.763\, lnG}{1 - 1.316\, lnG} \quad (8)$$

μ is the corresponding characteristic root and it can be expressed depending on the Biot number for a spherical object as follows:

$$\mu_1 = [1.1223\ln(4.9\,Bi + 1]^{1/1.4} \qquad 0 < Bi < 10 \quad (9)$$

$$\mu_2 = [(5/3)\ln(2.1995\,Bi + 152.4386]^{1/1.2} \qquad 10 < Bi < 100 \quad (10)$$

The moisture diffusivity for a spherical object is given by the following equation:

$$D_{eff} = \frac{S\,R_S^2}{\mu_1^2} \quad (11)$$

The coefficient of mass transfer on the surface (*k*) can be determined in the following equation:

$$k = \frac{Bi.D_{eff}}{R_S} \quad (12)$$

Since the cornelian cherry has an oval shape, the equivalent radius was calculated using the following equations [17];

$$R_S = \frac{3V}{S_P} = \left(\frac{3V}{S_S}\right)\left(\frac{S_S}{S_P}\right) = \Psi R_{eq} \quad (13)$$

$$S_P = 2\pi a^2 + \left(\frac{\pi b^2}{e}\right)\ln\left(\frac{1+e}{1-e}\right) \quad (14)$$

$$e = \left[1 - \left(\frac{b}{a}\right)^2\right]^{1/2}$$

$$\Psi = \frac{S_S}{S_P} \quad (15)$$

$$V = \frac{4}{3}\pi a^2 b$$

2.3.2. The thermal properties

The thermal conductivity values (k_m), density (ρ_m), and heat capacity (C_{pm}) for cornelian cherry were calculated depending on the moisture content using the equations given in Table 1 [18-20].

Table 1. Equations used to calculate the thermophysical properties of food depending on the moisture

Property	Equation
Density (kg/m³)	$\rho_m(X_t) = 147.95(X_t/X_0) + 691.46$
Heat capacity(J/kgK)	$C_{pm}(X_t) = 837 + 3348(X_t/(1 + X_t))$
Thermal conductivity (W/mK)	$k_m(X_t) = 0.49 - 0.44\exp(-0.206X_t)$

Thermal diffusivity is determined as follows:

$$\alpha_m = \frac{k_m}{\rho_m . C_{pm}} \quad (16)$$

2.3.3. The coefficients of convective mass and heat transfer

In a system with forced flow, engineering correlations involving the number of dimensionless are used to calculate the coefficients of convective mass and heat transfer. In this study, the Whitaker correlation (Eq. (17)) was chosen to calculate the coefficients of convective heat transfer for flow over the sphere [21].

$$Nu = 2 + (0.4\, Re^{1/2} + 0.06 Re^{2/3}) Pr^{0.4} (\mu_a/\mu_s)^{1/4} \quad (17)$$

This equation is valid for;

$3.5 \leq Re_p \leq 7.6x10^4$ $0.71 \leq Pr \leq 10$ 1.0≤μ_a/μ_w≤3.2

$$Nu = \frac{h\, R_s}{k_a} \quad (18)$$

$$Re_p = \frac{\rho_a . V_a . D_p .}{\mu_a} \quad (19)$$

$$Pr = \frac{v_a}{\alpha_a} \quad (20)$$

All thermophysical properties except μ_w for drying air were calculated at air temperature using the equations given in Table 2 [22].

Table 2. Equations used to determine the thermophysical properties of air

Property	Equation
Density (kg/m³)	$\rho_a = 353.12\, P/T$
Viscosity (Pa/s)	$\mu_a = 1.691x10^{-5} + 4.984x10^{-8}T - 3.187x10^{-11}T^2 + 1.319x10^{-14}T^3$ *(250K<T<400K)*
Thermal conductivity (W/mK)	$k_a = 7.78x10^{-5}T + 2.74x10^{-3}$ *(250K<T<400K)*
Water-air diffusivity (m²/s)	$D_{aw} = 1.963x10^{-7}T + 3.33307x10^{-5}$ *(293 K<T<373 K)*
Latent heat of water vaporization (J/kg)	$h_{fg} = 3.158x10^6 - 2.402x10^3T$ *(290 K ≤T ≤ 370K)*
Heat capacity (J/kgK)	$C_{pa} = 1.933x10^{-10}T^4 - 7.999x10^{-7}T^3 + 1.141x10^{-3}T^2 - 0.449T + 1057{,}3$ *(295 K < T < 800 K)*

The coefficient of mass transfer was calculated with the Chilton-Colburn analogy (j-factors) between the thermal and the boundary layers of concentration [23].

$$j_H = St_H Pr^{2/3},\ j_M = St_M Sc^{2/3},\quad j_H = j_M \Longrightarrow h_c = \frac{h\, D_{aw}}{k_a} Le^{1/3} \quad (21)$$

Le (Lewis number) and Sc (Schmidt number) are defined as follows:

$$Le = \frac{Sc}{Pr} = \frac{\alpha_a}{D_{aw}} \quad (22)$$

$$Sc = \frac{v}{D_{aw}} \quad (23)$$

2.3.4. The consumption and efficiency of energy

The total energy consumption *(EC)* of the convective dryer can be defined as the sum of the energies consumed by the heater (the thermal energy, E_{th}) and the fan (the mechanical energy, E_{mc}). Thermal and mechanical energy are determined using Eq. (24) [24, 25] and Eq. (25) [26].

$$E_{th} = A\, V\, q_a\, C_a\, \Delta T\, t \quad (24)$$

$$E_{th} = \frac{V^3}{16600} \quad (25)$$

$$EC = E_{th} + E_{mc} \quad (26)$$

The energy efficiency for a drying process is described as the ratio of the energy required to evaporate of moisture from the wet material to energy consumed by the dryer to perform this process. Energy efficiency can be calculated using Eq. (27) [27].

$$\eta_e = \frac{Q_w}{EC} \quad (27)$$

$$Q_w = h_{fg}\, m_w \quad (28)$$

$$m_w = \frac{m_0 (X_0 - X_f)}{100 - X_f} \quad (29)$$

Q_w (kJ) is the energy requirement to evaporate of moisture from the wet material. h_{fg} (kJ/kg) is the latent heat to remove of water, how it is calculated is given in Table 2.

2.3.5. The thermal efficiency

The thermal efficiency is the measure of how much of the thermal energy absorbed by a system is used as useful energy. For the drying system, thermal efficiency is the ratio of the latent heat of moisture in the material to be dried to the amount of energy requirement to remove of water from the free water. For the drying process, the thermal efficiency is calculated from the following equation [28]:

$$\eta_t = \frac{M\, A\, h_{fg} (X_0 - X_f)}{Z\, t\, (100 - X_f)} \quad (30)$$

2.3.6. The drying efficiency

The drying efficiency represents the ratio of the sum of the energy requirement to heat the sample to drying conditions and the energy required to remove of water from the wet material to energy consumption.

$$\eta_d = \frac{Q_w + Q_m}{EC} \quad (31)$$

$$Q_m = m_d\, C_{pm}\, (T_0 - T_i) \quad (32)$$

2.4. The statistical analysis

Dincer and Dost model parameters (*G* and *S*) were calculated by nonlinear regression analysis method using a software package program at a 95% confidence level (IBM SPSS 20). The coefficient of fit (R^2), chi-square (χ^2), error of square root mean (*RMSE*) and *P%* values were used to calculate the relationship between the model and experimental data. The basic criterion in determining the best model is that the R^2 value is close to 1. In addition, *RMSE* and χ^2 values close to zero and *P* value less than 10% were considered to have good compatibility.

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (X_{exp,i} - X_{pre,i})^2}{\sum_{i=1}^{N} (\bar{X}_{exp} - X_{exp,i})^2}, \qquad \bar{X}_{exp} = \frac{\sum_{i=1}^{N} X_{exp,i}}{N} \quad (33)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (X_{pre,i} - X_{exp,i})^2}{N}} \quad (34)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} (X_{pre,i} - X_{exp,i})^2}{N - z} \quad (35)$$

$$P\% = \frac{100}{N} \sum_{i=1}^{N} \frac{|(X_{pre,i} - X_{exp,i}|}{X_{exp,i}} \quad (36)$$

3. Results and discussion

3.1. The coefficients of mass transfer

The drying coefficients (S) and lag factors (G) were calculated by using the least squares method from the experimentally obtained data (MR and t) and the results were summarized together with statistical parameters in Table 3. Statistical results ($R^2 > 0.99$ and lower χ^2, RMSE, P%) showed that the exponential model described by Eq. (12) provided a good fit for all drying conditions of cornelian cherry. The compatibility of the experimental values and the MR values calculated from the model is given in Figure 2. As given in Table 3, the results of the models are in sensible fit with the experimental value.

The lag factor (G), is a function of the Biot Number. Also, it refers to the magnitude of external and internal resistors to both mass and heat transfer from the solid material. It has been reported important information that if the lag factor value is between 1 and 2 for spherical bodies, The Biot number between 0.1 and 100 shows that the external and internal resistors are effective [15]. As given in Table 3, the lag factor (G) is diverse between 1.052-1.126. These results showed that moisture diffusion in the cornelian cherry was controlled by both external and internal resistances.

In practical applications, internal and surface resistances are considered to be effective. The results for Bi support each other with the G values showing that both resistances are effective. Similar results were reported for saffron [29], passion fruit peel [30], and celeriac [31].

The drying coefficient (S) indicates the drying capacity of food in unit time. Values of drying coefficient were found to be in the range of $1.138\text{x}10^{-5}$- $4.549\text{x}10^{-5}$ s^{-1}. As given in Table 3, the drying coefficient increased by increasing drying air temperature and velocity. Increasing temperature enhances heat transfer from air to the fruit which causes an increase in the evaporation rate of moisture in the fruit. Increased air velocity causes a thinner boundary layer around the solid and this provides a better-quality heat transfer from air to fruit. These positive effects lead to an increase in the drying capacity of the fruit.

Table 3. The lag factor (G) and the drying coefficient (S) together with statistical parameters

V m/s	*T* °C	$\text{S}\text{x}10^5$	G	R^2	$\chi^2\text{x}10^4$	RMSE	%P
0.4	50	1.138	1.126	0.996	2.75	0.0163	1.422
	60	1.948	1.093	0.997	2.73	0.0161	1.435
	70	3.463	1.068	0.990	9.71	0.0298	2.743
0.7	50	1.259	1.118	0.988	9.53	0.0303	2.725
	60	2.369	1.086	0.997	2.04	0.0140	1.151
	70	4.549	1.062	0.995	4.92	0.0210	1.906
1.0	50	1.508	1.122	0.994	5.02	0.0220	1.944
	60	2.460	1.075	0.995	4.51	0.0220	1.795
	70	4.545	1.052	0.995	7.50	0.0206	2.372

The Biot number is an important dimensionless group. It explains the ratio of the internal conduction resistance inside the solid to the external convective resistor at the surface of the solid. The Biot number was calculated with Eq. (8) for all of the experimental parameters and the results are shown in Table 4. Biot numbers were in the range of 0.150-0.388 which indicates the presence of both external and internal resistors to the moisture diffusion of cornelian cherry fruit. Similar results were reported for apple slices [32], broccoli [33], and eggplant [34].

Moisture diffusion from solid material during drying is a very complicated mechanism. Variety theories, capillarity flow, thermal and molecular diffusion, hydrodynamic flow, etc., have been proposed to explain the moisture diffusion phenomenon in solids. The effective moisture diffusion coefficient (D_{eff}), which includes the interaction of these theories, is the most important parameter to control and improve the process since drying is usually controlled by internal diffusion [6].

Eq. (11) was used to determine the values of effective diffusivity of moisture and the results are given in Table 4. These values indicate that increasing air temperature and air velocity increased the values of D_{eff}. Air velocity is effective on the external conditions of the material to be dried. The increase in air velocity thins the stagnant layer on the fruit and provides a more effective heat transfer from the hot air to food. However, the effect of air temperature on D_{eff} was higher than air velocity. Increasing temperature is related to the evaporation rate of water in food.

The rising temperature increases the evaporation rate and vapor pressure of the moisture in the fruit. Moisture with rising vapor pressure moves faster in the pores of the fruit and leaves the fruit faster. The values of D_{eff} obtained for cornelian cherry ($3.142\text{x}10^{-10}$ to $3.22\text{x}10^{-9}$ m^2/s) are within the general between 10^{-11}-10^{-9} m^2/s in foodstuff [35]. Similar results obtained by using this model were reported foodstuff such as $7.52\text{x}10^{-10}$-$3.8\text{x}10^{-9}$ m^2/s for celeriac [31], $6.51\text{x}10^{-10}$-$1.67\text{x}10^{-9}$ m^2/s for mushroom [36] and $7.4\text{x}10^{-10}$-$7.26\text{x}10^{-9}$ m^2/s for whole lemon [33].

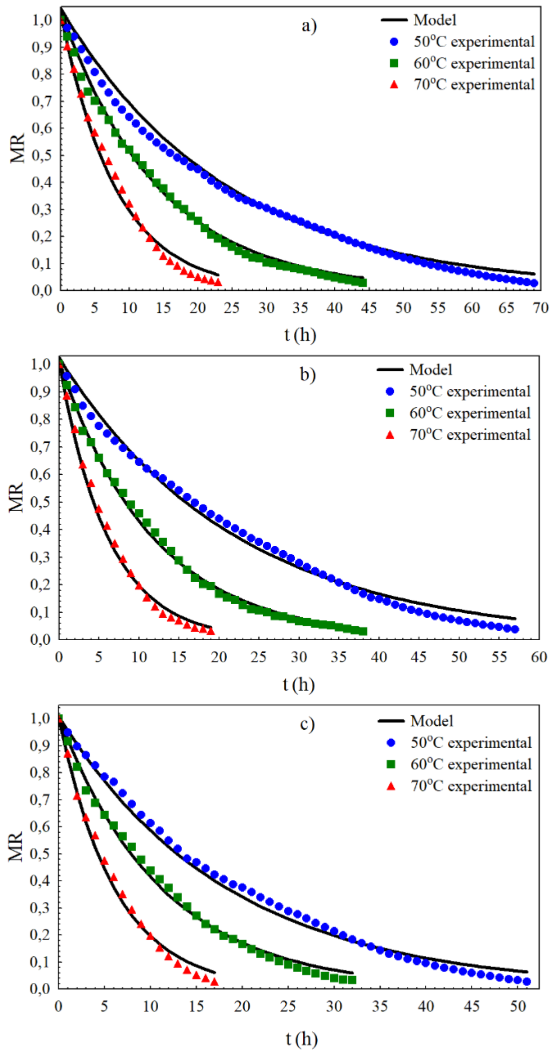

Figure 2. Model fits of theoretical and experimental X_t values according to the Weibull equation

The coefficient of mass transfer (k) in the boundary layer on the surface is an important parameter that depends on the properties of the fluid, drying conditions, and the geometry of the dried material. k values were determined from Eq. (12) and values are shown in Table 4. As given in Table 4, while k values increased with temperature, the velocity of air did not have a significant effect. This is an indication that increasing temperature increases the moisture transfer rate. These results are supported by the S and D_{eff} values [33, 37].

Table 4. The mass transfer and effective moisture diffusivity values

V m/s	*T* °C	*Bi*	*μ*	$D_{eff}\text{x}10^{10}$ m^2/s	$k\text{x}10^8$ m/s
0.4	50	0.388	1.136	3.142	6.129
	60	0.277	0.973	7.329	10.208
	70	0.199	0.824	18.164	18.136
0.7	50	0.361	1.101	3.704	6.726
	60	0.255	0.936	9.648	12.383
	70	0.179	0.780	26.636	23.945
1.0	50	0.374	1.118	4.298	8.087
	60	0.221	0.870	11.592	12.850
	70	0.150	0.709	32.234	24.264

3.2. Thermal properties

It was determined that approximately 95% of the moisture content in fruit was in the pulp of the fruit (Section 2.1). Therefore, it can be assumed that the moisture transfer in the fruit is only from the pulp.

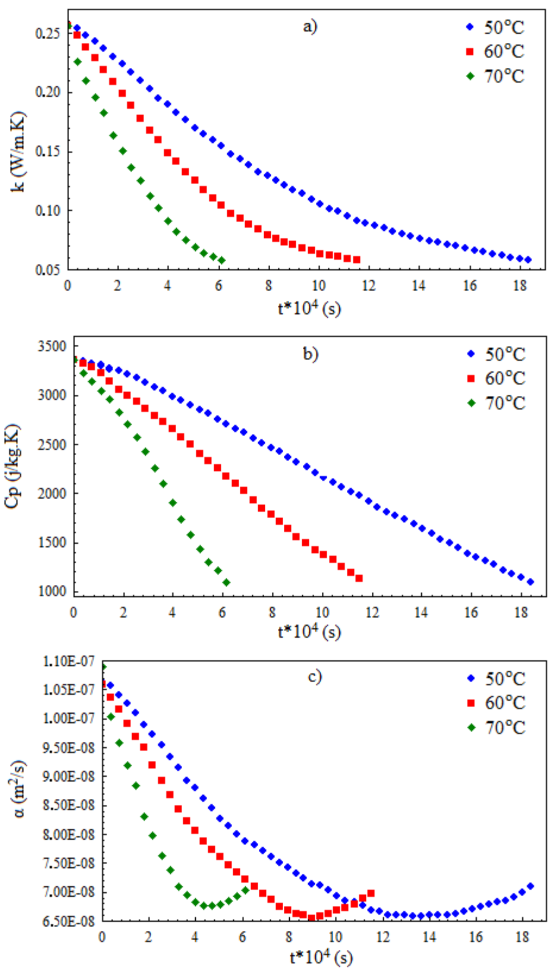

Figure 3. Variation of thermal properties versus time for 1 m/s air velocity (a. thermal conductivity b. heat capacity c. thermal diffusivity)

During the drying period, the thermophysical properties of the fruit such as thermal conductivity, heat capacity, and density, depending on the moisture content, were determined using the equations given in Table 1. Then, values of thermal diffusivity were determined using these thermophysical properties from Eq. (5). Figure 3 shows the time-dependent variation of heat capacity (C_{pm}), thermal conductivity (k_m), and thermal diffusivity (α_m) at 50, 60, and 70°C for 1 m/s air velocity (similar to other air velocities, not shown here) for cornelian cherry.

All of the thermal properties tend to decrease with time since moisture content decreases during the drying. According to Fig. 3, the highest values of C_{pm}, k_m, and α_m were obtained for fresh fruit as 3444 J/kgK, 0.487 W/mK, and 1.33x10^{-7} m^2/s, respectively. At the end of the drying period, the values of C_{pm}, k_m, and α_m reached their lowest values of 1110 J/kgK, 0.058 W/mK, and 7.03x10^{-8} m^2/s, respectively. These values were approximately the same for all experiment conditions since the fruits dried from the same initial moisture content (3.065 db) to the same final moisture content (0.09 db).

Water, which is present in high proportions in fresh fruit, is dispersed in the structure of the fruit. During the drying period, the water in the fruit evaporates and cavities are formed in the structure, and then formed cavities are filled with air. Since the heat capacity and thermal conductivity of water are much greater than those of air, it is an expected result that the thermal properties decrease with the decrease of moisture ratio.

The calculated average values of thermal diffusivity, heat capacity, and thermal conductivity for conditions of all experimental are given in Table 5. As shown in Table 5, the thermal properties decreased with increasing temperature and air velocity. This behavior can be explained that the vaporization rate of water in the fruits increases and the drying time decreases by increasing of velocity and temperature of air.

In a shorter drying time, the thermal properties decrease sharply as the moisture content decreases more rapidly. Therefore, the thermal properties and their average values also decrease. At low air velocity and temperatures, the drying time is longer and the evaporation of moisture is slower. Since the change in moisture content is small in periodic intervals, the calculated thermal properties will be big and close to each other. As a result of this, the average of the thermal properties are high. The results agree with those fecal sludge and orange slices [18, 38].

3.3. The coefficients of convective mass and heat transfer

To consider, the shrinkage effect of the fruit while calculating the Reynolds number, 5-6 fruits were taken from the dryer at certain periods and their measurement was made with a caliper. Diameters were calculated according to Eqs.(18-20). The average diameter was calculated from the diameters determined in each period. and the geometric mean of these diameters was used while calculating the *Re* number.

Table 5. Average values of heat capacity, thermal conductivity and thermal diffusivity

V m/s	*T* °C	C_{pm} J/kg.K	k_m W/m.K	α x10^8 m^2/s
	50	2062.27	0.108	7.175
0.4	60	1872.26	0.098	6.988
	70	1460.81	0.071	6.820
	50	2040.04	0.106	7.095
0.7	60	1805.43	0.095	6.986
	70	1300.60	0.065	6.789
	50	2005.55	0.103	7.044
1.0	60	1786.12	0.090	6.940
	70	1263.50	0.063	6.458

The coefficients values of the convective mass and heat transfer calculated for all experimental conditions are given in Table 6. As given in Table 6, while the effect of air temperature on the mass and heat transfer coefficients were negligible, the effect of air velocity on them was significant. In an increase from 0.4 m/s to 1.0 m/s of air velocity, the coefficients of mass and heat transfer increased by about 50% which was an expected result since coefficients are a function of the *Re* number. This observation is important because it shows the effect of air velocity on drying. Increasing air velocity not only causes higher heat and mass transfer coefficients but also thins the boundary layer, resistor to heat, and mass transfer, around the fruit. Thus, the quality of heat transfers from the air to food increases, and the drying time is reduced due to the faster evaporation of water from the fruit. The results are consistent with the transfer coefficients obtained for quince slices [23].

Table 6. The coefficients of convective heat and mass transfer on different air temperatures and velocities

V m/s	*T* °C	Re	Pr	Nu	Sc	Sh	h W/m^{2}K	h_c m/s
	50	211.40	0.723	8.978	0.750	9.321	21.13	0.023
0.4	60	200.26	0.720	8.765	0.744	9.052	21.15	0.024
	70	190.16	0.718	8.568	0.738	8.811	21.17	0.025
	50	369.96	0.723	11.472	0.750	11.912	27.00	0.030
0.7	60	350.45	0.720	11.182	0.744	11.548	26.98	0.031
	70	332.77	0.718	10.913	0.738	11.223	26.96	0.037
	50	528.51	0.723	13.520	0.750	14.038	31.82	0.035
1.0	60	500.65	0.720	13.166	0.744	13.597	31.77	0.036
	70	475.39	0.718	12.838	0.738	13.203	31.72	0.037

3.4. The energy consumption (EC)

The total energy consumption (*EC*) of convective drying of cornelian cherry for all experimental conditions is given in Figure 4. It was seen from Fig. 4 that *EC* increased with the increase of air velocity at each temperature and decreased with increasing temperature at each air velocity. In an increase from 0.4 m/s to 1.0 m/s of air velocity at 70°C, the EC increased from 24.60 MJ to 45.45 MJ. Likewise, when the air temperature increased from 50ºC to 70ºC for 0.4 m/s, the *EC* decreased from 46.95 MJ to 24.60 MJ. The highest value of energy consumption was obtained as 86.77 MJ at 50ºC air temperature, 1.0 m/s air velocity, and the lowest value of it was obtained as 24.60 MJ at 70ºC and 0.4 m/s air velocity.

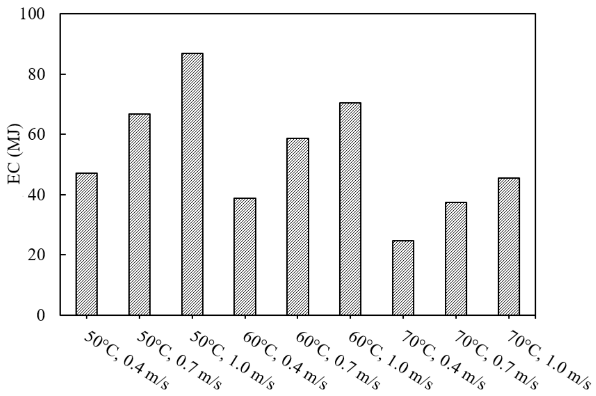

Figure 4. Energy consumption of experimental conditions of convective drying of cornelian cherry

The decrease in energy consumption with increasing temperature can be explained as follows: the energy of drying air increases with increasing temperature, the evaporation rate of the moisture in the fruit in contact with higher energy air increases, the drying time decreases and so the energy consumption decreases. The increase in energy consumption with air velocity can be associated with joint Eq. (24). The term of ρV (kg/m^{2}s) in Eq. (24) represents the mass flux of air entering the dryer. Increasing the air velocity will increase the air flux (the amount of air to be heated) and therefore higher energy consumption will be required to heat more air.

3.5. Energy efficiency, thermal efficiency, and drying efficiency

Energy, thermal, and drying efficiencies were calculated using Eqs. (24-29) and the results are summarized in Table 7. Energy efficiency increased when energy consumption decreased. Under operating conditions, the maximum energy efficiency was determined as 9.32% at 0.4 m/s air temperature and 70oC air temperature, while the minimum energy efficiency was determined as 2.70% at 1.0 m/s air speed and 50°C temperature. The results found for energy consumption and energy efficiency are in fit with the results reported for Roman chamomile [26] and green pea [39].

Table 7. Thermal energy and drying efficiency

V m/s	*T* °C	*t* min	Energy efficiency %	Thermal efficiency %	Drying efficiency %
0.4	50	4140	4.985	4.932	5.028
	60	2640	3.509	5.922	6.045
	70	1380	2.697	9.368	9.431
0.7	50	3360	5.980	3.428	3.539
	60	2280	3.956	3.954	3.998
	70	1200	3.289	6.126	6.191
1.0	50	3060	9.324	2.688	2.720
	60	1920	6.127	3.275	3.323
	70	1020	5.046	4.978	5.096

As given in Table 7, the efficiencies of thermal energy and drying depending on the parameters are similar to energy efficiency. Drying and thermal efficiencies decreased with increasing air velocity and increased with increasing temperature. While the maximum drying and thermal efficiencies values were 9.423 and 9.555, respectively at 70°C and 0.4 m/s, their minimum values were determined as 2.75 and 2.736, respectively at 50°C and 1.0 m/s. The values of energy and thermal efficiency were very close to each other. Drying efficiency was slightly higher than energy and thermal efficiency as some of the consumption energy was used to heat the fruit to drying temperature. In the convective drying process, similar results were determined for Roman chamomile and apple slices [26].

4. Conclusion

In this study, the dehydration of cornelian cherries was carried out by means of a convective dryer at various air speeds and temperatures. Using the drying data, the effects of air velocity and air temperature were evaluated from the perspective of heat and mass transfer coefficients, energy consumption, energy efficiency, and thermodynamic properties. Effective diffusivity (D_{eff}) was positively affected by enhanced air velocity and temperature. Since the thermal properties in terms of density, thermal diffusivity, heat capacity, and thermal conductivity values were functions of moisture content, they decreased with the decrease in moisture content during the drying period. With the increase in air velocity, the heat transfer coefficients, and convection mass increase, while the effect of temperature on these properties is negligible. Increasing air speed and decreasing temperature increased total energy consumption. The lowest total energy consumption value was obtained as 24.60 MJ at 70°C temperature and 0.4 m/s velocities of air. Energy and thermal efficiency values were found to be quite close to each other under drying conditions, but drying efficiency had higher values than both.

Nomenclature

MR	The moisture ratio
M_t	The moisture content at any time (g water/g dm)
M_e	The equilibrium moisture content (g water/g dm)
M_o	The initial moisture content (g water/g dm)
G	The lag factor (dimensionless)
S	The drying coefficient (s^{-1})
μ_1	The characteristic equation constant
D_{eff}	The effective moisture diffusivity (m^2/s)
R	Radius (m)
t	Time (s)
k	The mass transfer coefficient (m/s)
R_s	Radius of the sphere (m)
k	The mass transfer coefficient (m/s)
R_{eq}	The equivalent radius of cornelian cherry (m)
V	Volume (m^3)
S_p	The surface area of cornelian cherry (m^2)
S_s	The surface area of the sphere (m^2)
a,b	The major minor semi-axes of rotating ellipse
e	Eccentricity
Ψ	Shape factor
h	Convective heat transfer coefficient (W/m^{2}k)
C_{pm}	The heat capacity (kj/kgk)
k_m	The thermal conductivity (W/mk)
D_{aw}	Diffusivity coefficient of water-air (m^2/s)
E_{th}	Thermal energy (kj)
E_{mc}	Mechanical energy (kj)
A	Area (m^2)
ΔT	The temperature difference of air (°C)
η_e	Energy efficiency
Q_w	Energy required (kj)
h_{fg}	The latent heat of evaporation (kj/kg)
X_o	The first moisture content (g water/g dm)
X_f	The final moisture content (wb)
m_w	The material water content (g)
m_d	The weight of dry material (kg)
m_o	Initial mass of material (kg)
Z	Utilized capacity of the heating source (kw)
M	Loading density of material (kg/m^2)
T_o	Outlet temperature (K)
T_i	Inlet temperature (K)
η_d	Drying efficiency
Q	Energy required to evaporate (kj)
k_B	Boltzmann constant (1.3806x10^{-23} J/K)
h_p	Planck's constant (6.6262x10^{-34} Js)
R	Universal gas constant (8.314 J/molk)
P	Atmospheric pressure (atm)
K	Kelvin
St_H	Nu/(re.pr)
St_M	Sh/(re.sc)

Dimensionless

Bi	Biot number for mass transfer
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
St_H	Stanton number for heat transfer
Sc	Schmidt number
Le	Lewis number
J_H	Chilton-Colburn-*j*-factor heat transfer

Gree Greek letters

ρ	The density of material (kg/m^3)
v	The kinematic viscosity (m^2/s)
α	The thermal diffusivity (m^2/s)
μ	The dynamic viscosity(kg/ms)

Subscripts

a	Air	Dm	Dry matter
d	Dry	Wb	Wet basis
db	Dry base	M	Material
w	Wet material		

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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