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An analytical method for determining the temperature dependent moisture diffusivities of pumpkin seeds during drying process

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Abstract

This paper presents an analytical method, which determines the moisture diffusion coefficients for the natural and forced convection hot air drying of pumpkin seeds and their temperature dependence. In order to obtain scientific data, the pumpkin seed drying process was investigated under both natural and forced hot air convection regimes. This paper presents the experimental results in which the drying air was heated by solar energy.

Keywords: Diffusion coefficient; Temperature dependence; Moisture diffusivity

1. Introduction

Moisture transport is an important parameter in many applications ranging from food engineering to preservation of agricultural products. One of the examples for the latter case is pumpkin seeds. Most widely used preservation process after the harvest of various moist biological and agricultural products is to dry them with hot air.

In general, drying takes place in two stages. In the first phase, drying occurs on the product surface at a constant rate as if the product is uniform in composition. This process is similar to the evaporation of water in an open environment. Amount of evaporated water largely depends on the environmental conditions rather than the conditions and the nature of the product composition. In the second phase, drying takes place at a decelerating rate, which is imposed by the properties of the dried product. The most suitable condition for drying is when the moisture is present in the outer hard layer surface as a thin film layer. This moisture can be easily transported from the product by the drying process. This mechanism can be effective until the air is reached the saturation point [1]. Moisture may also be present in the capillaries of the product, within its porous media, or in its crystalline structure. Mohr [2] and Hemming [3] have reported that it is necessary to transport this moisture to the surface of the product.

With a thin liquid film, a shell with a rough surface texture and a unique shape pumpkin seed drying is strongly dependent on the temperature of the hot air [4,5]. Pumpkin seeds laid in a single layer on drying sieves, were dried both under natural and forced-convection regimes. In the first case, ambient air was used for drying. For the latter case a test chamber was constructed [6,7]. Test chamber consisted of solar energy heated air circulation that through the sieve trays in the cabinet. Test results were used to plot the changes in the unit moisture mass per dried product mass as a function of time.

In this study, the main objective was to investigate the variation of the drying processes with constant diffusion coefficient approach. Then, data were obtained using six different temperature measurements in the drying process. Half of the temperature measurements were taken under natural convection conditions and the rest were taken

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Nomenclature

A	flow cross-section, m^2	o	orifice ratio
A_n	n dependent coefficient	P	pressure, Pa
B_n	n dependent coefficient	t	time interval, h
C	non-dimensional concentration coefficient	$\dot{V}$	volumetric flow rate, m^3/s
D	diffusion coefficient, m^2/h		
Fi	Fick's number	*Greek symbols*	
m	mass, kg	Pi	number
M_n	n dependent coefficient	ρ	mass density, kg/m^3
N	power, kW	Y	half-length of the model
		X	dry product based moisture content (kg moisture/kg dry product)
Subscripts			
A	starting value	NU	moist product related
DE	at equilibrium moisture	o	orifice
Eff	effective	ort	average
K	duct	t	in time units
KU	dry product	a	specific instant
m	non-dimensional average	y	direction in the Cartesian coordinate system
n	iteration number		

under forced convection conditions. Later, analytical calculations were carried out for the same natural and forced convection data.

2. Analysis

In general, capillary fluid flow model, which has been applied to products with seeds and porous media, has yielded good results, and indicates that it can be successfully applied to pumpkin seed drying, too Can [5]. The main assumption in this model is the condition that thermal presence is much higher than humidity presence. This assumption makes it possible to ignore temperature gradients in the product during drying. According to this model, the Effective Humidity Diffusion Coefficient, D_{eff}, characterizes multi variable moisture diffusion process, which takes place from the core of the product towards its surface by capillary forces. Eq. (1) gives the second Fick's Law for one-dimensional unsteady-state moisture diffusion process.

$$\frac{\partial C}{\partial t} = -D\frac{\partial^2 C}{\partial y^2} \tag{1}$$

Then, Gealsk [4] and Krischner [8] have made the investigations on drying. Mohr and others have determined that, it is an advantageous to express the unsteady concentration which with a trigonometric series expansion [10]:

$$C_m = \sum_{n=0}^{\infty} A_n \cdot B_n \cdot \exp(-M_n^2 \cdot Fi) \tag{2}$$

Here, Eq. (3) can express the non-dimensionless average concentration coefficient.

$$C_m = \frac{m_{\text{DE}} - m_{\text{t}}}{m_{\text{DE}} - m_{\text{A}}} \tag{3}$$

where Fick's number is

$$Fi = \frac{D \cdot t}{Y^2} \tag{4}$$

Mohr and others mentioned that number of terms in Eq. (2) might be determined for drying problem in question by using Fick's condition. For example, it has been reported that the first three terms are sufficient to describe the drying process of small seeded products. In an infinite expanding plate, Eq. (1) may be used to describe the non-dimensionless average concentration, as given in Eq. (5)

$$C_{m,Y} = \frac{m_{\text{DE}} - m_{\text{t}}}{m_{\text{DE}} - m_{\text{A}}} = \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2\pi^2} \exp\left(-\frac{(2n+1)^2\pi^2}{4}\frac{D \cdot t}{Y^2}\right) \tag{5}$$

From this equation, for one dimensional moisture transfer, average product moisture at any given time t may be defined as follows:

$$m_{\text{t}} = m_{\text{DE}} + (m_{\text{A}} - m_{\text{DE}}) \cdot C_{m,Y} \tag{6}$$

Iglesias [9] and Mohr [10] have reported that it is necessary to calculate the equilibrium moisture mass, m_{DE}, in order to determine the coefficients of the applicable equation for products with three dimensional plate forms. m_{DE} may be determined either from the sorption isotherms or by experimental techniques.

3. Experimental set-up

In the present study, pumpkin seed-drying behaviour was experimentally investigated. A solar air collector was

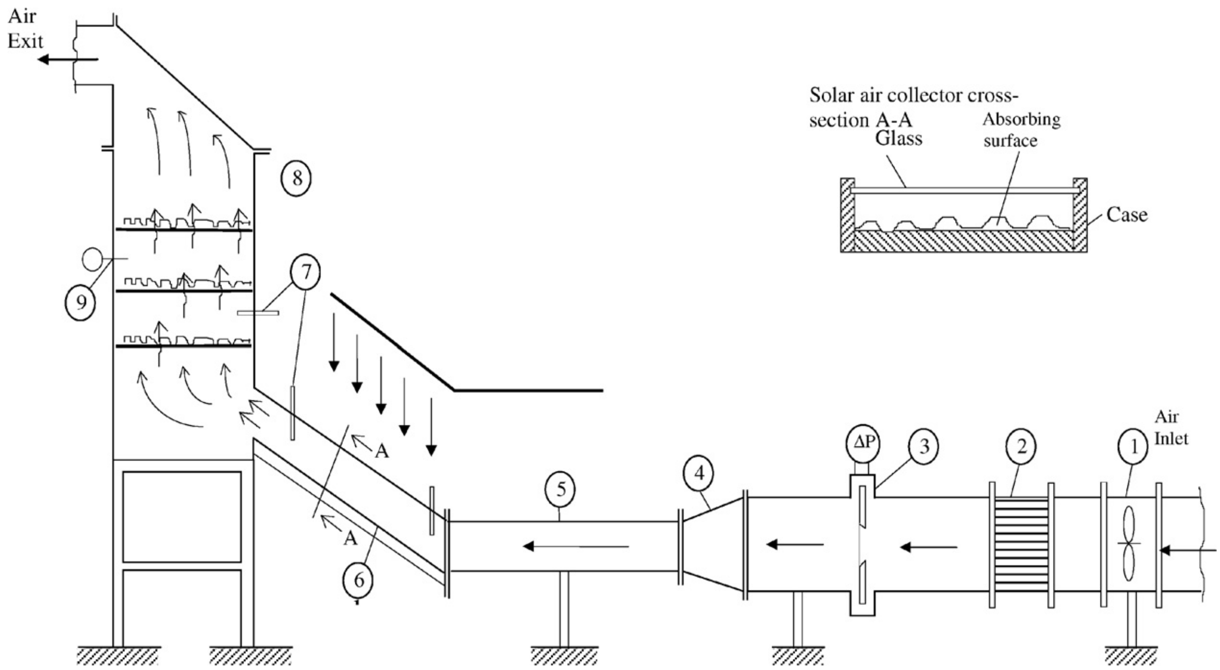

Fig. 1. Experimental set-up and test equipment. 1: Air fan, 2: Honeycomb, 3: Orifice, 4: Cross section change, 5: Flow stabilizers, 6: Solar air heating collector, 7: Temperature sensor, 8: Dryer trays, 9: Humidity sensor. Distance of drying trays: 150 mm.

used for drying purposes. During the experiments, three sieves were used and 3 kg of pumpkin seed were placed into each sieve.

Fig. 1 shows the experimental set-up and the test equipment used.

Drying air was circulated from bottom to top of the cabin through the pumpkin seed batch. During the process, change in moisture of pumpkin seed was determined every hour by measuring the mass by a scale. At the same time, some pumpkin seeds were dried with natural convection in the open tray.

Experimental set-up and test equipment used in this study were as follows:

Air fan: $V = 0.055\ \mathrm{m^3/s}$, max; pressure difference $\Delta P = 1900$ Pa and power $N = 2$ kW.

Standard Orifice: Orifice diameter $d_o = 75$ mm, orifice ratio $o = (A_{go}/A_K =)$ 0.56. According to DIN (1952),

$$V = \alpha \varepsilon_o A_K \sqrt{2\Delta P}/\rho \tag{7}$$

Measured ΔP was converted to V.

Humidity meter: One EBRO brand Hygrometer RH T 100 with ±1% accuracy within the 3% and 98% RH range. The same instrument measures the temperature with ±0.1 °C accuracy within the −100 °C and +200 °C range.

Electronic balance: Precise 6200D, 0–6200 g range, ±1 g accuracy.

Temperature measurement device: One EBRO brand RH T 100 digital temperature measurement device and six Model TX-500, digital thermometers in the −50 °C and 1200 °C range, *K* Type (CA) Sensors, Input resistance 100 kΩ, Accuracy: (Less thermocouple sensor's error), ±0.5% of the reading, ±0.35% of f.s.

Power source: 9 V(6F22) battery.

4. Drying behavior of pumpkin seed

At the beginning of the experiment, 9 kg of the most humid pumpkin seeds were loaded from the batch into three drying trays with sieves (3 kg product in each tray). Hot drying air was passed through the drying trays from the bottom. Humidity contents were measured by recording the change in mass of the pumpkin seed with 1 h intervals. For control purposes another set of samples from the same batch were used, which were naturally dried simultaneously on an open tray in the ambient. Moisture content of this set was also recorded in the same manner. Humidity of the drying air has been recorded both at the solar collector entrance and in the drying cabinet. Air velocity in the 100 mm diameter pipe between the fan and cross-section change was measured with AIRFLOW TA2 analog manometer. During the experiments $\Delta h = 7$ mm, 11 mm, and 15 mm water column values measured on the U manometer which were adjusted prior to test by regulating the air flow rates to $0.051\ \mathrm{m^3/s}$, $0.043\ \mathrm{m^3/s}$, $0.035\ \mathrm{m^3/s}$ respectively. Within this volumetric flow rates average cabinet air temperatures were measured as 40 °C, 43 °C, and 46 °C. X_{DE} equilibrium moisture for pumpkin seeds was determined experimentally [5,6]. For this purpose, another sample from the same batch with maximum moisture content was tested in the same set-up for a 48 h period until the end of drying process was observed. Then m_{DE} was

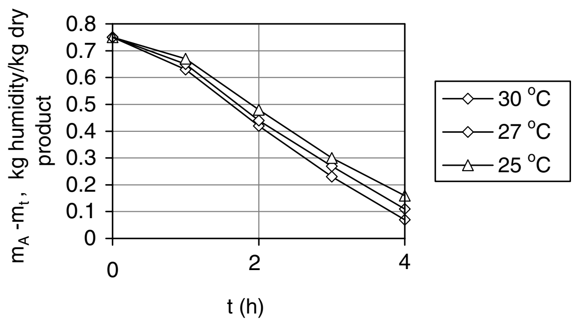

Fig. 2. Temperature dependence of pumpkin seed drying with natural convection.

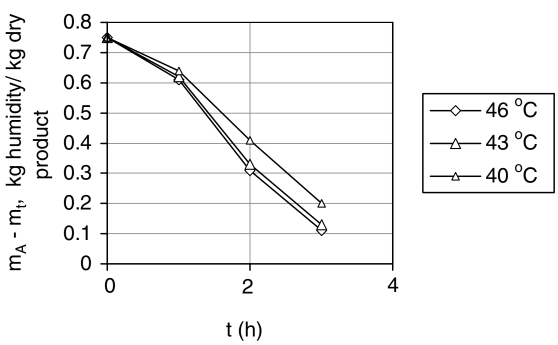

Fig. 3. Temperature dependence of pumpkin seed drying behaviour by forced convection.

calculated by weighing this sample. Then another sample with the same m_{DE} value was completely dried in a sterilizer at 120 °C, for 24 h, which gives the completely dried mass m_{ku}. From the following equation,

$$X_{DE} = (m_{DE} - m_{ku})/m_{ku} \tag{8}$$

X_{DE} is 0.07 (kg moisture/kg dry product). The initial moisture of the product to be dried is 0.61 (kg humidity/kg dry product), from the following equation:

$$X_{ku} = (m_{NU} - m_{ku})/m_{ku} \tag{9}$$

Experimental results are shown in Fig. 2 for natural convection and in Fig. 3 for forced convection (see Tables 1 and 2).

Table 1
Experimental data and calculation results for drying with natural convection

t (°C)	$x(\frac{1}{T}\times 10^3)$	$y(D_{eff})$
Natural convection drying		
30	3.30	1.230×10^{-6}
27	3.33	1.336×10^{-6}
25	3.35	1.427×10^{-6}
$\sum x_i = 9.98$	$\sum y_i = 4.619\times 10^{-10}$	
$\sum x_i^2 = 33.2$	$\sum x_i y_i = 15.364\times 10^{-10}$	
$\sum x_i^3 = 110.458$	$\sum y_i x_i^2 = 51.104\times 10^{-10}$	
$\sum x_i^4 = 367.501$		

Table 2
Experimental data and calculation results for drying with forced convection

t (°C)	$x(\frac{1}{T}\times 10^3)$	$y(D_{eff})$
Forced convection drying		
46	3.134	1.086×10^{-6}
43	3.164	1.119×10^{-6}
40	3.194	1.225×10^{-6}
$\sum x_i = 9.492$	$\sum y_i = 4.768\times 10^{-10}$	
$\sum x_i^2 = 30.036$	$\sum x_i y_i = 15.083\times 10^{-10}$	
$\sum x_i^3 = 95.04$	$\sum y_i x_i^2 = 47.713\times 10^{-10}$	
$\sum x_i^4 = 300.773$		

5. Determination of the effective moisture diffusion coefficient

According to Mohr, in the first decreasing drying rate range presence of a constant diffusion can be tested by checking the change in $\log(X_t - X_{DE})$ with the drying time t. Fig. 4 shows the corresponding plot for free convection for 25 °C, 27 °C and 30 °C. Using the slope of the lines in Fig. 4, D_{eff} may be determined Mohr [2,10]. Fig. 5 is repeated for forced-convection data as shown in Fig. 5 for 40 °C, 43 °C and 46 °C.

Determination of diffusion coefficient: Pumpkin seed particle is modeled as a $7(z)\cdot 15(x)\cdot 3(y)$ mm, rectangular

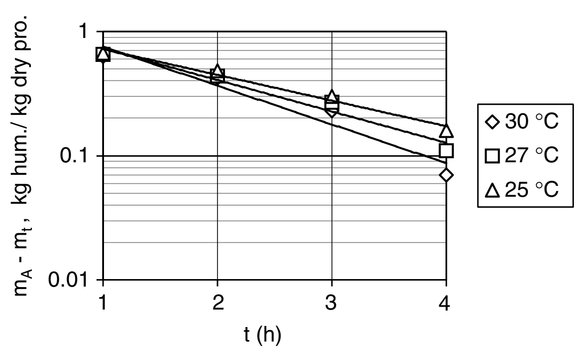

Fig. 4. Change of diffusion coefficient in natural convection drying with temperature.

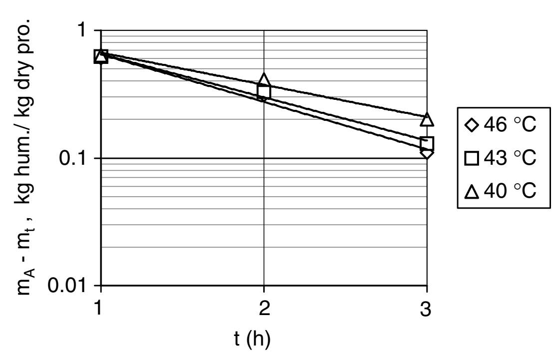

Fig. 5. Change of diffusion coefficient in forced convection drying with temperature.

prism. For the given model, when drying takes place only in the y-direction, C_{my} non-dimensional concentration was expressed in terms of y coordinate using Eqs. (2) and (5). So far, there has no diffusion coefficient value available in the literature. A computer program was written for Eq. (5) in order to provide a valid coefficient under experimental working conditions. The experimentally determined C_{my}, corresponding to the half of the measured 3 mm, i.e. $Y = 1.5$ mm and to the five terms of the trigonometric series, i.e. $n = 0, 1, 2, 3, 4$, and t values for every corresponding C_{my} were included in this computer program. The computer program was executed by an iterative technique by assuming a, D value at the beginning. In Eq. (5), the right hand side was changed until it became equal to C_{my} on the LHS, which yields D_{eff} values of 1.225×10^{-6} m^2/h, 1.119×10^{-6} m^2/h and 1.086×10^{-6} m^2/h for forced convection at 40 °C, 43 °C, and 46 °C. In natural drying conditions open to ambient with trays in a single layer pumpkin seed arrangement, at 25 °C, 27 °C, and 30 °C drying conditions the respective D_{eff} values were 1.427×10^{-6} m^2/h, 1.336×10^{-6} m^2/h and 1.230×10^{-6} m^2/h.

6. Temperature dependence of diffusion coefficient

Experimental results were used to determine the temperature dependence through various techniques. In this study, polynomial regression method was used to fit polynomials both for the natural and forced convection cases. Least Squares method may be extended to higher order polynomials [11]. For example, assuming that a second order polynomial or a quadratic equation is fitted in the form of

$$y = a_0 + a_1 x + a_2 x^2 \tag{10}$$

When the square of the residuals are summed

$$S_r = \sum (y_i - a_0 + a_1 x_i + a_2 x_i^2)^2 \tag{11}$$

Equating the derivatives of this term with respect to the unknown coefficients to zero

$$\begin{aligned} &(n)a_0 + \left(\sum x_i\right)a_1 + \left(\sum x_i^2\right)a_2 = \sum y_i \\ &\left(\sum x_i\right)a_0 + \left(\sum x_i^2\right)a_1 + \left(\sum x_i^3\right)a_2 = \sum x_i y_i \\ &\left(\sum x_i^2\right)a_0 + \left(\sum x_i^3\right)a_1 + \left(\sum x_i^4\right)a_2 = \sum x_i^2 y_i \end{aligned} \tag{12}$$

Sum is from $i = 1$ to n. Each linear equation has three coefficients a_o, a_1, and a_2. These unknowns can be solved by using the experimental data. Here the correlating equation is $T(K) = t\,(°C) + 273$, $x((1/T) \times 10^3)$ and $y(D_{\text{eff}})$ were used. Polynomial is second order and n is 3. Results for both natural and forced-convection are given below.

Using the above figures and writing Eq. (12) first for natural convection and then for forced convection two different systems of equations are obtained, which were solved by Cramer's method.

For natural convection:

$$\begin{aligned} D_{\text{eff}}(t) = {}& 5.755 \times 10^{-6} - 4.273 \times 10^{-7}\left(\frac{1}{t+273}\right) \\ & - 2.713 \times 10^{-8}\left(\frac{1}{t+273}\right)^2 \end{aligned} \tag{13}$$

For forced convection:

$$\begin{aligned} D_{\text{eff}}(t) = {}& 6.237 \times 10^{-6} + 4.197 \times 10^{-7}\left(\frac{1}{t+273}\right) \\ & - 6.414 \times 10^{-7}\left(\frac{1}{t+273}\right)^2 \end{aligned} \tag{14}$$

7. Conclusions

This method can be expanded for different agricultural products under the steady or the un-steady state conditions. As mentioned in the end of section "determination of the effective moisture diffusion coefficient", a model, which is rectangular prism was considered for three temperature values, forced convection and the others, natural convection experimentally. The values obtained are given in Figs. 2 and 3. Then, D diffusion coefficient is calculated for each time intervals in Eq. (5), and average values are obtained. The calculated moisture concentration values, using average diffusion coefficient for all process, are compared with the values given in Figs. 2 and 3. In addition, it has been obtained that the results can be harmonious. The results have been shown that the model and the analytical method provide an accurate means of calculating the moisture distribution, moisture diffusion coefficients, and their dependence on temperature for practical purposes. For a controlled drying of pumpkin seeds, a model is also essential for the moisture diffusion, besides the kinematics model. The theory prescribed with the model explained in this study has been validated with experimental results, which revealed two different expressions for drying of pumpkin seed for natural and forced-convection cases with solar energy heated air.

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