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Drying Characteristics of Strawberry Fruit Leather

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Abstract: The effects of air temperature and sample thickness on drying kinetics of strawberry leather were investigated. The mathematical modeling was performed by using three thin-layer dying models. The independent variables were sample thickness (S1 = 1.8, S2 = 2.7, and S3 = 3.6 mm) and air temperature (50, 60, 70, and 80°C). All samples took place in the falling rate period. The values of effective moisture diffusivity, D_{eff} varied from 2.40 to 12.1 × 10-9 m^2/s depending on drying conditions. The values of activation energy, E_a were 35.57, 33.14, and 30.46 kJ/mol for each sample of S1, S2, and S3. The two-term exponential model was found to satisfactorily describe the thin-layer drying kinetics of strawberry leather.
Keywords: strawberry leather, drying, mathematical modeling, diffusivity, activation energy

Introduction

Fruit leather is a confectionery product manufactured by dehydrating fruit puree into leathery sheets. It is made by drying thin layers of fruit puree in the oven or dehydrator to produce a product with the texture of soft leather. These leathery sheets called sometimes as fruit rolls or taffies are nutritious snacks for backpackers, campers, and children. Many kinds of fruit or combinations of fruit can be used: apricots, apples, grapes, berries, pineapple, oranges, pears, peaches, plums, tomatoes, tropical fruits, and others. Especially, fruit leathers add value to fruit, which may otherwise not acceptable for the fresh produce market. Strawberries as a typical soft fruit have a high physiological postharvest activity with short ripening and senescence periods that make marketing of this high quality fruit a challenge. Thus, one of the most promising methods for preservation would be to manufacture the strawberry leather by drying. Drying is the most commonly employed commercial technique in the food processing industry. It involves the vaporization of moisture within the product by heat and its subsequent evaporation from the product (Ekechukwu 1999). Thus, a drying process involves simultaneous heat and mass transfer. Many types of dryer are available to the food industry.

Drying methods are usually classified into four categories depending on heat transfer mechanism into product such as convection (Azzouz and others 2002; Dandamrongrak and others 2002; Krokida and others 2003), conduction (Fudym and others 2003), radiation (Abe and Afzal 1997; Fu and Lien 1998; Afzal and Abe 2000) and microwave heating (Adu and Otten 1996). Convection drying is one of the most common unit operations in the food processing industry. It relies on heating the product by contact with hot air. The drying behavior is greatly affected by air temperature and material characteristic dimension. Understanding drying kinetics of fruit leather is very important for the control of the drying process and quality of final product. Although many studies have been carried out to the influence of some process parameters such as drying air temperature and sample thickness for various foods (Madamba and others 1996; Youcef-Ali and others 2001; Doymaz 2004), a few of works have reported for some fruit leathers (Chan and Cavaletto 1978; Cheman and others 1997; Maskan and others 2002), but none for strawberry leather. The objectives of this study were to (1) investigate the effect of process parameters such as drying air temperature and sample thickness on the drying kinetics of strawberry leather, and (2) to find out suitable mathematical model for the drying curves.

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Materials and Methods

Materials

Strawberry puree was obtained from Sensient Flavors Inc. (Amboy, IL, USA) and pectin (SS200) was from Danisco USA, Inc. (St. Louis, MO, USA). Corn syrup and citric acid of anhydrous fine granular were purchased from ADM (Decatur, IL, USA).

Experimental Procedure

Strawberry leathers were prepared by blending strawberry puree, corn syrup, pectin, and citric acid in 200:40:2:1 ratios, spreading into thin layers on an aluminum weighing dish of 70mm diameter (Fischer Scientific, Pittsburgh, PA), and drying in a convection oven (OV116040, M & L Testing Equipment Inc., Canada). The independent variables were product thickness (1.8, 2.7, and 3.6 mm) and drying temperature (50, 60, 70, and 80℃). Moisture losses were recorded by an electronic balance (APX-1502, Denver Instrument, USA) with a sensitivity of 0.01 g at constant time intervals during drying for the determination of drying curves. Drying tests were replicated three times, and averages are reported. Initial moisture content of strawberry leather was determined by drying ten samples of each 10 g in a convection oven at 100℃ for 24 h and then, measuring the masses of samples after cooled in a desiccator with silica gel for 30 min. The average initial moisture content of strawberry leather was 51.35% (wb) or 105.55% (db). This value was used to determine the drying rate under every experimental condition. Drying data were evaluated by nonlinear regression program (SigmaPlot 2000, SPSS Inc., Chicago, IL).

It has been generally accepted that drying phenomenon of biological materials is controlled by the mechanism of moisture diffusion during the falling rate period. Fick's law of diffusion has been frequently used to describe the internal moisture transfer during drying for homogeneous materials, in which the heterogeneity of the material is taken into account by the use of an effective diffusivity. With the assumption of moisture migration being by diffusion, negligible shrinkage, and constant diffusion coefficients and temperature, the solution of Fick's equation for a semi-infinite slab is as follows (Crank, 1975):

$$MR=\frac{(M-M_e)}{(M_o-M_e)}=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\pi^2}{4L^2}D_{eff}t\right] \quad (1)$$

where MR is the dimensionless moisture ratio, M is the average moisture content (db) at time t (s), M_o is the initial moisture content (db), M_e is the equilibrium moisture content (db), D_{eff} is the effective diffusivity (m^2/s), and L is the half thickness of sample (m). To predict the drying rate of shelled con fully exposed to air, Sharaf-Eldeen and others (1980) presented a two-term diffusion model, which is a part of an infinite series of Eq. (1). This model applies regardless of product geometry and boundary conditions. However, it requires constant product temperature and assumes constant diffusivity. This two-term exponential model is written in the form:

$$MR=\frac{(M-M_e)}{(M_o-M_e)}=A_1\exp(-k_1t)+A_2\exp(-k_2t) \quad (2)$$

where A_1, A_2, k_1, and k_2 are the empirical coefficients.

Mathematical Model

A simple model analogous to Newton's law of cooling, also termed the Lewis model (Lewis 1921) is often used in drying analysis to describe the falling rate period during thin-layer drying of products (Temple and van Boxtel 1999; Phoungchandang and Woods 2000; Panchariya and others 2002). It assumes that the rate of moisture removal is proportional to the difference between products being dried and its equilibrium moisture content. It is mathematically expressed as:

$$\frac{dM}{dt}=-k(M-M_e) \quad (3)$$

or the solution of this equation after integrating can be written as:

$$MR = \frac{(M - M_e)}{(M_o - M_e)} = \exp(-kt) \quad (4)$$

where k is the drying constant (s^{-1}).

The Page model that is a modification of the Lewis equation to overcome its shortcomings has been widely used in thin-layer drying studies (Chen and Wu 2001; Panchariya and others 2002; Doymaz and Pala 2003; Doymaz 2004). It is written in this form:

$$MR = \frac{(M - M_e)}{(M_o - M_e)} = \exp(-k_o t^m) \quad (5)$$

where k_o is the drying constant (s^{-m}) and m is the drying exponent. The dimensionless moisture ratio, MR of Eqs. (1), (2), (4), and (5) can be simplified to M/M_o, because the values of the equilibrium moisture content, M_e are relatively small to M or M_o (Doymaz 2004).

Aalysis of the drying data and drying models

The Lewis model, the Page model, and the two-term exponential models were fitted to the drying data for describing the drying curves of strawberry leather (Table 1). Calculated moisture ratio and drying time were used in fitting the models. The coefficient of determination, r^2 is one of the primary criteria to select the best model to account the validation of drying curve (Madamba and others 1996; Chen and Wu 2001; Dandamrongrak and others 2002; Panchariya and others 2002). In addition of r^2, the reduced chi-square (χ^2) has been widely used to determine the goodness of fit of the tested thin-layer drying models to experimental data (Pangavhane and others 1999; Sarsavadia and others 1999; Midilli and Kucuk 2003; Lahsasni and others 2004). Chi-square can be calculated in equation form as:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{cal,i})^2}{N - n} \quad (6)$$

where $MR_{exp,i}$ is the experimental moisture ratio at the ith observation , $MR_{cal,i}$ is the calculated moisture ratio at this observation, N is the number of observations, and n is the number of constants. The lower values of χ^2, and the higher values of r^2 were chosen as the criteria for the best of the fit. In this study, the relationships among the drying air temperature, sample thickness, and the coefficient of the tested drying models were determined.

Table 1 Mathematical models applied to the drying curves

Model description	Model
The Lewis model	$MR = \exp(-kt)$
The Page model	$MR = \exp(-k_o t^m)$
Two-term exponential model	$MR = A_1 \exp(-k_1 t) + A_2 \exp(-k_2 t)$

Results and Discussion

Influence of process variables

The effects of drying air temperature and sample thickness on draying rate of strawberry leather were investigated with neglecting shrinkage of product. The drying data involving percentage moisture content (db) were transformed to the dimensionless parameter of moisture ratio (MR) and plotted versus drying time (t). Figure 1 shows the typical characteristic drying curves for strawberry leather of 2.7 mm thickness during thin-layer drying process at 50, 60, 70, and 80℃. Increase of the drying temperature markedly affected an increase in the drying rate with decreasing drying time. Similar results were obtained for sample thicknesses of 1.8 and 3.6 mm. Figure 2 presents the effect of sample thickness on drying rate at 60℃. The decrease of sample thickness at constant drying temperature reduced significantly the drying time needed to equilibrium moisture content. Similar trends were observed at drying temperatures of 50, 70, and 80℃. Based on these results, drying times for strawberry leather samples to reach the moisture content of 12% (wb) for safe storage were found to vary from 80 to 600 min depending on drying temperature and sample thickness (Table 2).

Drying times of 55.6, 66.7, and 70% were reduced for each sample thickness of 1.8, 2.7, and 3.6 mm as drying temperature was raised from 50 to 80 ℃. Similarly, the deceases in drying time of 55.6, 61.5, 66.7, and 70.0% were observed at each drying temperature of 80, 70, 60, 50 ℃ with decreasing sample thickness from 3.6 to 1.8 mm. It was considered that the influence of thinner sample thickness on drying time was due to reduced distance of moisture movement and the increased surface area exposed for a given volume of product. The pronounced effects of temperature and sample thickness on drying time were similar to studies on garlic slices (Madamba and others 1996), chicory root slices (Lee and Kang 2001), grape leather (Maskan and others 2002), and carrot cubes (Doymaz 2004).

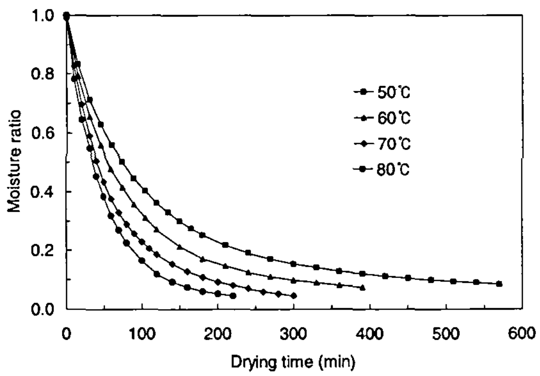

Fig. 1 Drying curves at different drying temperatures for strawberry leather of 2.7 mm thickness.

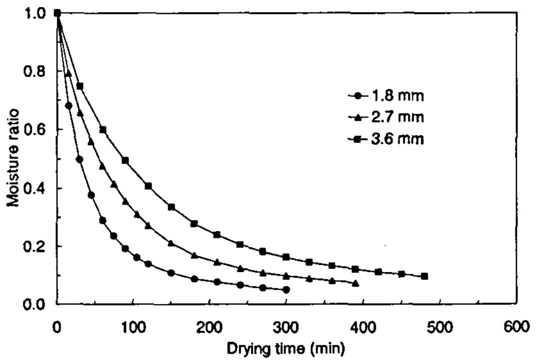

Fig. 2 Drying curves for different sample thicknesses of strawberry leather at 60℃.

Table 2 Drying time (min) for samples of strawberry leather to reach the moisture content of 12% (wb)

Sample thickness	Temperature			
	50℃	60℃	70℃	80℃
S_1 (1.8 mm)	180	120	100	80
S_2 (2.7 mm)	360	240	180	120
S_3 (3.6 mm)	600	360	260	180

Calculation of the effective moisture diffusivity and activation energy

The drying rate (d*M*/d*t*) was calculated from the slops of the moisture content against drying time curves. Figure 3 presents the drying rate curves at different temperatures, which shows the variation of the drying rate versus moisture content. It was observed that the initial drying rate was high and followed by a gradual decrease as product approached to dried state. As the thickness of sample decreased from 3.6 to 1.8 mm, drying rates increased with the drying rate curves shifted upwards for each drying air temperature investigated (Figure 4). Similarly, higher drying rate during drying was found at higher temperature. In this study, the drying of strawberry leather occurred almost in the falling rate period. The results were generally in good agreement as compared to previous works on thin -layer drying of various biological products (Madamba and others 1996; Lee and Kang 2001; Maskan and others 2002; Akpinar and others 2003; Lahsasni and others 2004). Drying during the falling rate period is internally controlled with diffusion being the moisture movement mechanism because of the decreasing rate of moisture needed for evaporation from the drying surface with time. The results of this study indicated that diffusion is the most likely physical mechanism governing moisture movement in strawberry leather during thin-layer drying.

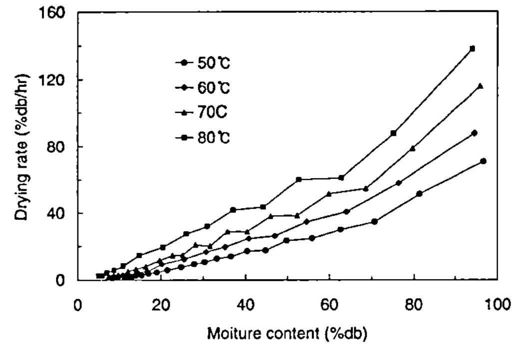

Fig. 3 Drying rate curves at different drying temperatures for strawberry leather of 2.7mm thickness.

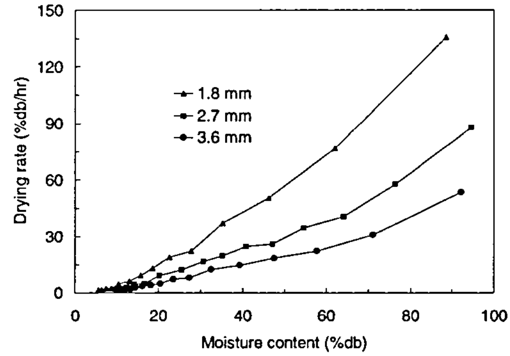

Fig. 4 Drying rate curves for different sample thicknesses of strawberry leather at 60℃.

The solution of Fick's diffusion equation developed for semi-infinite slab can be used to describe the drying of strawberry leather. For long drying times (MR<0.6), the first term (n = 0) of Eq. (1) is obtained and expressed in a logarithmic form (Madamba and others 1996; Maskan and others 2002; Demirel and Turhan 2003):

$$\ln MR = \ln\frac{M - M_e}{M_0 - M_e} = \ln\frac{8}{\pi^2} - D_{eff}t\left(\frac{\pi}{2L}\right)^2 \quad (7)$$

A more general form of Eq. (7) is expressed as follows:

$$\ln MR = \ln\frac{M - M_e}{M_0 - M_e} = A - Bt \quad (8)$$

where constant, B is related to the effective diffusivity:

$$B = \frac{D_{eff}\pi^2}{4L^2} \quad (9)$$

The linear relationships were obtained by plotting the moisture ratio (MR) and drying time (t) on the semi-logarithmic scale (Figure 5) at different drying temperatures for strawberry leather of 2.7mm thickness in accordance with Eq. (8). Figure 6 shows the drying rate curves plotted for different sample thicknesses at 60℃. In this study, straight lines were satisfactorily fitted to the experimental data with r^2>0.97 at all drying temperature and sample thickness investigated. The effective diffusivity was calculated by Eq. (9), using slops derived from the linear regression of ln(MR) versus time (t) for different drying conditions.

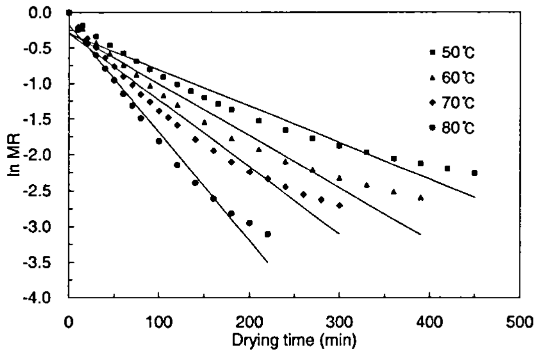

Fig. 5 Semilogarithmic plots of drying curves at different drying temperatures for strawberry leather of 2.7mm thickness.

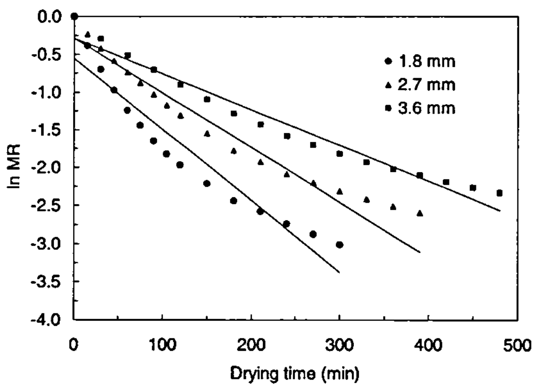

Fig. 6 Semilogarithmic plots of drying curves for different sample thicknesses of strawberry leather at 60℃

The values of D_{eff} estimated for different sample thickness and temperature were presented in Table 3 with r^2. Both of the drying air temperature and sample thickness had a pronounced influence on the drying rate and as a result, greatly affected the value of D_{eff}. The values of D_{eff} for strawberry leather ranged from 2.40 to 12.10 × 10^{-9} m^2/s depending on drying conditions. The higher value of D_{eff} was obtained at higher drying air temperature and thicker sample. These values are comparable to 1.533 - 2.885 ×10^{-9} m^2/s for air drying of paprika at 60℃ (Ramesh and others 2001), 2.25 - 2.74 ×10^{-8} m^2/s for red pepper at 60℃ (Doymaz and Pala 2002), and 0.776 - 9.335 ×10^{-9} m^2/s for carrot cubes in temperature range of 50 - 70℃ (Doymaz 2004).

Table 3 The values of effective diffusivity (m^2/s) for drying of strawberry leathers (D_{eff} × 10^9)

Sample thickness	Temperature							
	50°C	r^2	60°C	r^2	70°C	r^2	80°C	r^2
S_1 (1.8 mm)	2.40	0.94	3.09	0.94	4.68	0.95	7.32	0.97
S_2 (2.7 mm)	3.77	0.96	5.36	0.96	6.91	0.97	11.10	0.99
S_3 (3.6 mm)	4.57	0.97	6.24	0.96	8.38	0.97	12.10	0.98

The effect of temperature on effective diffusivity is generally described by a Arrhenius-type equation:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \quad (10)$$

where D_o is a constant equivalent to the effective diffusivity at infinite high temperature (m^2/s), E_a is the activation energy (kJ/kg), R is the gas constant (kJ/kmol·K), and T is the temperature of air (K). The activation energy for diffusion was calculated from the slop of straight line by plotting ln(D_{eff}) versus the reciprocal of the air temperature, $1/T$ (Madamba and others 1996; Maskan and others 2002; Panchariya and others 2002; Doymaz and Pala 2003). Figure 7 presents the linear relationships between ln(D_{eff}) and $1/T$ in the range of temperatures investigated for each sample thickness indicating Arrhenius dependence. The activation energy calculated from the slop of straight line of Figure 7 was found to be 35.57 (r^2 = 0.98), 33.14 (r^2 = 0.98), and 30.46 (r^2 = 1.0) kJ/mol for strawberry leather samples with 1.8, 2.7, and 3.6 mm thickness, respectively. The value of activation energy was increased with decreasing sample thickness. It showed the same trend with the results of Maskan and others (2002), which reported the E_a values of 10.3 - 21.7 kJ/mol depending on the sample thickness. This result suggested that thinner sample had greater sensitivity of diffusion than thicker sample against the temperature. The values of activation energy in this study were within the general range of 15 - 40 kJ/mol for various food materials (Rizvi, 1986).

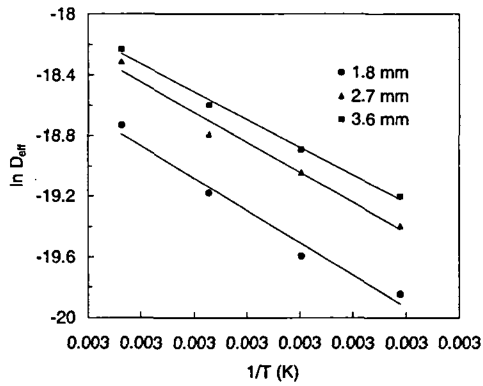

Fig. 7 Arrheius-type relationships between effective diffusivity and temperature for different sample thicknesses of strawberry leather

Modeling of the Drying Curves

Non-linear regression analysis was performed to fit drying curves to the data on the basis of the Lewis, the Page, and the two-term exponential models. These models for the best fit were evaluated with the coefficient of determination

(r^2) and chi-square (χ^2). Table 4 presents the drying constants, coefficients, and the values of r^2 and χ^2 of these three models. Each value of r^2 and χ^2 for these models were varied in the range of 0.9534 - 0.9997 and 2.6391×10^{-5} - 2.9731×10^{-3}. From these results, the Lewis and the Page models might be acceptable, but the two-term exponential model gave the best result in fitting the drying data with r^2 of 0.9991 - 0.9997 and χ^2 of 2.6391 - 9.2577×10^{-5}. Thus, the two-term exponential model could sufficiently define the air drying of strawberry leather. These results were similar to those of Madamba and others (1996) in garlic slices, Dandamrongrak and others (2002) in bananas with various pre-treatments, and Lahsasni and others (2004) in prickly pear fruit.

Table 4 Results of non-linear regression obtained from different thin-layer drying models

Model	T (°C)	Sample	Model constants	r^2	χ^2
The Lewis model	50	S_1	$k = 0.0137$	0.9558	2.8896×10^{-3}
		S_2	$k = 0.0080$	0.9534	2.9731×10^{-3}
		S_3	$k = 0.0049$	0.9540	2.6914×10^{-3}
	60	S_1	$k = 0.0197$	0.9701	2.2066×10^{-3}
		S_2	$k = 0.0110$	0.9706	2.1767×10^{-3}
		S_3	$k = 0.0068$	0.9714	1.9158×10^{-3}
	70	S_1	$k = 0.0238$	0.9757	1.7097×10^{-3}
		S_2	$k = 0.0141$	0.9778	1.5459×10^{-3}
		S_3	$k = 0.0089$	0.9782	1.4425×10^{-3}
	80	S_1	$k = 0.0328$	0.9935	7.9269×10^{-4}
		S_2	$k = 0.0191$	0.9935	5.4204×10^{-4}
		S_3	$k = 0.0120$	0.9903	7.3472×10^{-4}
The Page model	50	S_1	$k_o = 0.0929, m = 0.5785$	0.9863	1.4004×10^{-3}
		S_2	$k_o = 0.0494, m = 0.6315$	0.9917	7.4201×10^{-4}
		S_3	$k_o = 0.0326, m = 0.6555$	0.9939	4.2218×10^{-4}
	60	S_1	$k_o = 0.1212, m = 0.5705$	0.9893	1.4735×10^{-3}
		S_2	$k_o = 0.0563, m = 0.6508$	0.9912	8.6502×10^{-4}
		S_3	$k_o = 0.0356, m = 0.6840$	0.9942	6.4287×10^{-4}
	70	S_1	$k_o = 0.1003, m = 0.6443$	0.9924	8.6003×10^{-4}
		S_2	$k_o = 0.0577, m = 0.6836$	0.9928	6.9469×10^{-4}
		S_3	$k_o = 0.0376, m = 0.7112$	0.9951	4.4546×10^{-4}
	80	S_1	$k_o = 0.0918, m = 0.7287$	0.9941	5.6536×10^{-4}
		S_2	$k_o = 0.0470, m = 0.7856$	0.9946	4.1130×10^{-4}
		S_3	$k_o = 0.0367, m = 0.7642$	0.9961	3.7068×10^{-4}
Two-term exponential model	50	S_1	$A_1 = 0.7292, k_1 = 0.0236, A_2 = 0.2644, k_2 = 0.0038$	0.9997	2.6391×10^{-5}
		S_2	$A_1 = 0.6370, k_1 = 0.0147, A_2 = 0.3475, k_2 = 0.0028$	0.9992	5.9905×10^{-5}
		S_3	$A_1 = 0.6074, k_1 = 0.0097, A_2 = 0.3790, k_2 = 0.0020$	0.9991	6.2971×10^{-5}
	60	S_1	$A_1 = 0.7404, k_1 = 0.0321, A_2 = 0.2547, k_2 = 0.0058$	0.9997	3.0356×10^{-5}
		S_2	$A_1 = 0.6855, k_1 = 0.0180, A_2 = 0.3011, k_2 = 0.0038$	0.9992	7.3255×10^{-5}
		S_3	$A_1 = 0.6497, k_1 = 0.0121, A_2 = 0.3408, k_2 = 0.0028$	0.9992	5.9695×10^{-5}
	70	S_1	$A_1 = 0.6778, k_1 = 0.0403, A_2 = 0.3145, k_2 = 0.0094$	0.9995	4.6014×10^{-5}
		S_2	$A_1 = 0.6724, k_1 = 0.0223, A_2 = 0.3118, k_2 = 0.0055$	0.9992	6.2075×10^{-5}
		S_3	$A_1 = 0.6846, k_1 = 0.0143, A_2 = 0.3041, k_2 = 0.0036$	0.9994	4.9785×10^{-5}
	80	S_1	$A_1 = 0.6705, k_1 = 0.0488, A_2 = 0.3285, k_2 = 0.0165$	0.9997	3.0918×10^{-5}
		S_2	$A_1 = 0.5583, k_1 = 0.0290, A_2 = 0.4296, k_2 = 0.0114$	0.9991	9.2577×10^{-5}
		S_3	$A_1 = 0.7167, k_1 = 0.0172, A_2 = 0.2753, k_2 = 0.0054$	0.9995	5.0337×10^{-5}

The multiple regression analysis was performed to estimate the relationships between the drying constants and temperature and sample thickness of the two-term exponential model. Base on this analysis, the model and drying constants (k_1, k_2) were expressed in terms of the drying temperature (T) and sample thickness (S) as follows:

$$MR = \frac{(M - M_e)}{(M_o - M_e)} = 0.6691\exp(-k_1 t) + 0.3209\exp(-k_2 t) \quad (11)$$

where

$$k_1 = 14.3470\exp\left\{-0.5\times\left[\left(\frac{T-140.3217}{56.9824}\right)^2 + \left(\frac{S+16.6942}{5.7751}\right)^2\right]\right\} \quad (12)$$

$$k_2 = 3.3574\exp\left\{-0.5\times\left[\left(\frac{T-291.0162}{65.9699}\right)^2 + \left(\frac{S-0.4991}{1.9671}\right)^2\right]\right\} \quad (13)$$

Each value of r^2 and χ^2 was 0.9956 and 9.9359×10^{-7} for k_1 and 0.9827 and 5.0352×10^{-7} for k_2. Therefore, the two-term exponential model with the drying constants as a function of temperature and sample thickness could satisfactorily describe the thin-layer drying kinetics of the strawberry leather due to their high of r^2 and low of χ^2. The accuracy of this model was evaluated by comparing experimental data of moisture ratio with predicted values. Figure 8 presents the fit of Eq. (11) to the experimental data of the thin-layer drying for the 2.7 mm sample thickness of strawberry leather at different temperatures. There was a good agreement between predicted and observed values. Similar results were obtained for the 1.8 and 3.6 mm sample thicknesses at different drying temperatures.

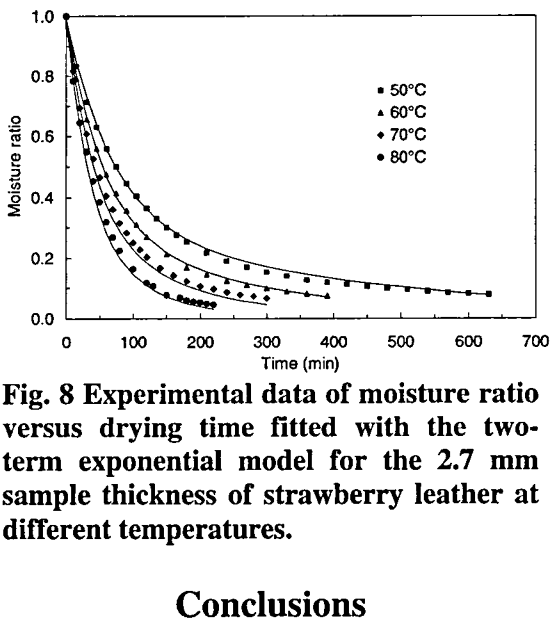

Fig. 8 Experimental data of moisture ratio versus drying time fitted with the two-term exponential model for the 2.7 mm sample thickness of strawberry leather at different temperatures.

Conclusions

Thin-layer drying kinetics of strawberry leather was investigated during air drying. The drying rate curves showed that drying of strawberry leathers for all samples took place in the falling rate period. The values of diffusivity followed an Arrhenius-type temperature dependence. Both drying air temperature and sample thickness had pronounced influences on diffusivity values. The values of activation energy for moisture diffusion were markedly affected by the sample thickness of strawberry leather. The two-term exponential model was found to give the best results in fitting the experimental data of strawberry leather as compared to other models. Drying constants of this model were correlated well with the temperature and sample thickness. Consequently, the two-term exponential model with the drying constants as a function of temperature and sample thickness could satisfactorily describe the thin-layer drying kinetics of the strawberry leather.

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