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Drying Kinetics of Onion Slices in a Hot-air Dryer

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Abstract

Onion slices were dehydrated in a single layer at drying air temperatures ranging from 50～70°C in a laboratory scale convective hot-air dryer at an air velocity of 0.66 m/s. The effect of drying air temperature on the drying kinetic characteristics were determined. It was found that onion slices would dry within 210～460 min under these drying conditions. Moisture transfer during dehydration was described by applying the Fick's diffusion model and the effective diffusivity changed between 1.345×10^{-8} and 2.658×10^{-8} m^2/s. A non-linear regression procedure was used to fit 9 thin layer drying models available in the literature to the experimental drying curves. The Logarithmic model provided a better fit to the experimental drying data as compared to other models. Temperature dependency of the effective diffusivity during the hot-air drying process obeyed the Arrhenius relationship with estimated activation energy being 31.36 kJ/mol. The effect of the drying air temperature on the drying model constants and coefficients were also determined.

Key words: drying, hot-air, kinetics, onion, thin-layer, models

INTRODUCTION

Onion (*Allium cepa* L.) is considered as one of the most important and widely consumed crops in many countries (1-3) and its production ranks third in the world (4). Onion is semi-perishable and has a short storage life. Dehydration is the one of the simplest ways to improve the shelf-life of fruits and vegetables by reducing the moisture content (5).

Dehydration operations are important steps in food processing industry, which involves a process of moisture removal due to simultaneous heat and mass transfer. Drying provides a longer shelf-life to the food, cheaper transportation cost, and smaller space demand during storage (6,7). Dehydrated onion has become a standard food ingredient in a wide range of food products (8) such as ketchup, soups, salad dressings, sausage and meat products, potato chips, crackers, and many other convenience foods (9).

A deep knowledge of the drying process and an adequate simulation model are required for use in process design, optimization, and control. In other words, drying systems must be properly designed so as to meet specific drying requirements of particular vegetables and to give satisfactory performance. Simulation models are needed for design development and for optimal operation of the drying systems. Although several studies have reported in the literature on the drying behavior of onion (2,4,6,7,10-12), no sufficient information is available on the drying kinetics of onion slices during conventional air-drying which is the most frequently used dehydration operation in food and chemical industries.

The objectives of present work were to determine the effect of drying temperature on drying characteristics of onion slices; to evaluate a suitable drying model for describing the drying process; and to compute effective moisture diffusivity and activation energy of samples.

MATERIALS AND METHODS

Materials

Fresh and fully matured white onions (*Allium cepa* L.) were obtained from Changnyeong-Gun, Korea and kept in cold storage at 4～5°C. Prior to dehydration, onions were thoroughly washed to remove the dirt after peeling manually. Sliced (*ca.* 63.7 mm in diameter) onions were obtained by carefully slicing at right angle to the vertical axis with the help of a sharp knife. The diameter and thickness of the slices were measured using a vernier caliper.

Experimentation

The experiments were carried out in batch mode at different drying air temperatures (50, 60, and 70°C) and an air velocity of 0.66 m/s. The temperatures were controlled by means of thermostats. Samples (3 slices, 4 mm in thickness) were immediately weighed and placed into a hot-air dryer (FOL-2, Jeio Tech Co., Incheon,

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Korea) without any pre-treatments. The average weight of the samples used was 41.04 g. Moisture losses of samples were recorded at 10 min intervals for 210～460 min depending on the air temperature. It was considered that dry product obtained equilibrium condition with the atmosphere inside the drying chamber when a constant weight was maintained for three consecutive weighings. That moisture content was considered as equilibrium moisture content. Each experiment was replicated three times and the average values were used for analysis.

Development of mathematical models

Hot-air drying is commonly used to reduce moisture in biological products. One way to represent a fundamental drying behavior is to consider the variation of drying rate against moisture content (13). The moisture content values for all the samples were transformed to dimensionless moisture ratios assuming the final moisture content to be the equilibrium moisture. The drying rate and the moisture ratio (*MR*) of onion slices during the thin layer drying experiments were calculated using the following equations:

$$Drying\ rate = \frac{M_{t+dt} - M_t}{dt} \tag{1}$$

$$MR = \frac{M - M_e}{M_o - M_e} \tag{2}$$

where, M, M_o, M_e, M_t and M_{t+dt} are the moisture content at any time, initial moisture content, equilibrium moisture content, moisture content at t and moisture content at $t+dt$ (kg water/kg dry matter), respectively, and t is drying time (min).

The initial moisture content of the onion samples was determined by vacuum drying at 70°C for 24 hr (14). The average initial moisture content of the slices was around 10.70 g water per g dry matter.

Empirical models: Nine well-known thin-layer drying models in Table 1 (15-23) were tested to select the best model for describing the drying curve of the onion slices. Non-linear least square regression analysis was performed using the Levenberg-Marquardt procedure of the SigmaPlot computer program. The coefficient of determination (R^2) was the primary criterion for selecting the best model to describe the drying curve. In addition, mean relative percent deviation (*EMD*), root mean square error (*RMSE*), and the reduced chi-square (χ^2) were used to determine the goodness of fit. These parameters can be calculated as follows:

$$EMD = \frac{100}{N}\sum_{i=1}^{N}\frac{|MR_{pre,i} - MR_{\exp,i}|}{MR_{\exp,i}} \tag{3}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^2\right]^{1/2} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N - z} \tag{5}$$

where, $MR_{exp,i}$ is the ith experimentally observed moisture ratio, $MR_{pre,i}$ the ith predicted moisture ratio, N the number of observations, and z is the number of the constant in model. The model was considered best when *EMD*, *RMSE,* and χ^2 were at minimum values and R^2 at a maximum value.

Diffusion model: The drying process of onion slices was found to have taken place in a falling rate period only. Therefore, the drying rate is limited by a moisture diffusion process and can be described by the Fick's second law of unsteady state diffusion given in Eq. (6). The solution of Fick's second law in slab geometry, with the assumptions of moisture migration being by diffusion, negligible shrinkage, constant diffusivity was follows as in Eq. (7) (24):

$$\frac{\partial M}{\partial t} = \nabla\left[D_{eff}(\nabla M)\right] \tag{6}$$

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{eff}\,t}{4L^2}\right) \tag{7}$$

where, D_{eff} is the effective moisture diffusivity (m^2/s),

Table 1. Selected drying models for describing onion drying data

No.	Model name	Model	References
1	Newton	MR=exp(-*kt*)	O'Callaghan et al. (15)
2	Page	MR=exp(-kt^n)	Page (16)
3	Modified Page	MR=exp((-*kt*)^n)	Overhults et al. (17)
4	Henderson and Pabis	MR=*a* exp(-*kt*)	Henderson and Pabis (18)
5	Logarithmic	MR=*a* exp(-*kt*)+*c*	Yagcioglu et al. (19)
6	Two term	MR=*a* exp(-*kt*)+*b* exp(-k_0t)	Henderson (20)
7	Two-term exponential	MR=*a* exp(-*kt*)+(1-*a*) exp(-*kat*)	Sharaf-Eldeen et al. (21)
8	Approximation of diffusion	MR=*a* exp(-*kt*)+(1-*a*) exp(-*kbt*)	Sharaf-Eldeen et al. (22)
9	Modified Henderson and Pabis	MR=*a* exp(-*kt*)+*b* exp(-*gt*) + *c* exp(-*ht*)	Karathanos (23)

L the half thickness of slab (m) (2,7). For long drying periods, Eq. (7) can be further simplified to only the first term of the series:

$$MR = \frac{8}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}\,t}{4L^2}\right) \tag{8}$$

The effective moisture diffusivity was calculated from a slope of a straight line by plotting experimental drying data in terms of ln(*MR*) vs. drying time as follows:

$$\text{Slope} = -\frac{\pi^2 D_{eff}}{4L^2} \tag{9}$$

The effect of temperature on the effective moisture diffusivity is often expressed using simple Arrhenius-type relationship:

$$D_{eff} = D_0\exp\left(-\frac{E_a}{RT}\right) \tag{10}$$

where, D_0 the pre-exponential factor of Arrhenius equation (m^2/s), E_a the activation energy (kJ/mol), R the universal gas constant (8.314×10^{-3} kJ/mol·K), and T the absolute temperature (K). The activation energy was calculated by plotting the natural logarithm of D_{eff} versus reciprocal of the absolute temperature.

RESULTS AND DISCUSSION

Effect of drying air temperature on moisture ratio of onion slices

The onion slices were dried as single layers with thicknesses of 4 mm at the drying air temperatures of 50, 60, or 70°C in a convective hot-air dryer. The onion slices had initial moisture contents of around 10.70 g water per g dry matter was dried to the final moisture content of about 0.83 g water per g dry matter until a constant weight at three consecutive reading was attained. Fig. 1 present the variations in the dimensionless moisture ratio as a function of drying time at various drying air temperatures.

The moisture ratio of onion slices decreased exponentially with the drying time, which is typical for food stuffs (7). It can be seen that the drying air temperature had a significant influence on the moisture ratio of samples. In other words, the increase in drying air temperature resulted in a decrease in drying time. As a result, the drying curves became steeper inducing higher moisture removal.

The drying times required to reach the final moisture content were 460, 320, and 210 min at the drying air temperatures of 50, 60, and 70°C, respectively. Several researchers have reported similar decreases in drying time with increases in the drying air temperature during hot-air drying of single arpicot (25), red chillies (26), pumpkin slices (27), and apple pomace (28).

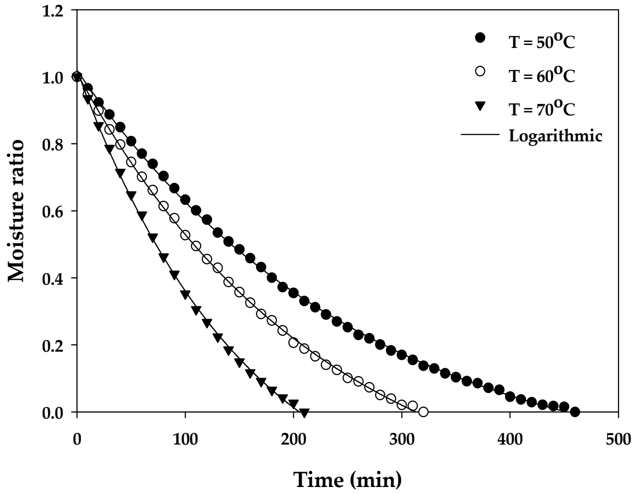

Fig. 1. Experimental thin-layer drying curves with computed moisture ratios obtained using the Logarithmic model at different air temperatures.

Effect of drying air temperature on drying rate

Drying rates of the onion slices were calculated using Eq. (1). Fig. 2 shows the changes in drying rate as a function of moisture content at various drying air temperatures. It is apparent that drying rate decreases continuously with increasing drying time or decreasing moisture content. Sliced onions did not exhibit a constant-rate drying period and all the drying operations are seen to occur in the falling rate period. This is due to the quick removal of moisture from the skin of onion slices and shows the diffusion-dominant drying phenomena. At the beginning of the drying process, drying rate was very high, and drying rate continued to decrease

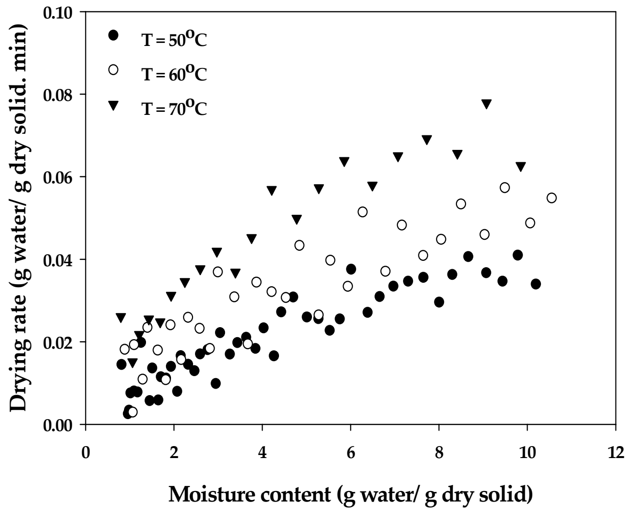

Fig. 2. Variation of drying rate with moisture content.

as moisture content approached the equilibrium moisture content. Similar results have been presented for aromatic plants (29), single apricot (25), mushrooms (30), red chillies (31), red pepper (32), and onion slices (2,33).

The drying rate increased with increased drying air temperature. The drying rate was higher for onion slices dried at higher temperature than the onion slices dried at lower temperature for the same average moisture content of the onions. Because the onion drying consists of a falling rate period, the effect of differences in the partial vapor pressure between onions and their surrounding is not considered to be dominant. This is partially responsible for the higher moisture transfer rate with higher temperature drying air.

Evaluation of the models

The average moisture ratios of onion slices at various drying air temperatures viz., 50, 60, and 70°C (Fig. 1) were fitted in selected thin-layer drying models in Table 1. The drying model coefficients and the comparison criteria used to evaluate goodness of fit, the values of coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (*RMSE*) for proposed models are presented in Table 2. Based on the criteria of the highest R^2 and the lowest *EMD*, *RMSE,* and χ^2 values, the best model describing the thin-layer drying characteristics of onion slices was selected. For all experiments, all models gave R^2 values greater than 0.98. From Table 2, the highest R^2 values and the lowest *RMSE* and values were obtained from the Logarithmic model followed by the Page model. Accordingly, the Logarithmic model was selected as suitable model to describe the thin-layer hot-air drying behavior of onion slices.

Fig. 1 also shows the variations of experimental and predicted moisture ratios by the Logarithmic drying model with drying time at the drying air temperatures of 50, 60, and 70°C. It can be seen that the proposed model provided a good conformity between experimental and predicted moisture ratios. This indicates the suitability of the Logarithmic drying model in describing hot-air drying behavior of onion slices.

Fig. 3 indicates the comparison of the predicted and the experimental moisture ratio values for various drying temperatures. The established model gave a good agreement between the predicted and the experimental mois-

Table 2. Estimated values of parameters of selected models used for thin-layer drying of onion slices at different temperatures

Model No.	Temp. (°C)	Model constants	R^2	χ^2	*RMSE*	*EMD*
1	50	*k*=0.0055	0.9910	0.0020391	0.0009979	51.68
	60	*k*=0.0073	0.9890	0.0027295	0.0013234	54.45
	70	*k*=0.0109	0.9874	0.0033531	0.0016003	42.51
2	50	*k*=0.0012, *n*=1.2786	0.9986	0.0038166	0.0001868	24.64
	60	*k*=0.0015, *n*=1.3188	0.9978	0.0005592	0.0002711	21.87
	70	*k*=0.0020, *n*=1.3730	0.9983	0.0004960	0.0002367	13.25
3	50	*k*=0.0051, *n*=1.0640	0.9910	0.0033535	0.0016003	42.57
	60	*k*=0.0069, *n*=1.0718	0.9890	0.0027293	0.0013233	52.59
	70	*k*=0.0101, *n*=1.0786	0.9874	0.0020401	0.0009984	53.96
4	50	*k*=0.0059, *a*=1.0766	0.9938	0.0014071	0.0006886	44.05
	60	*k*=0.0079, *a*=1.0760	0.9918	0.0020404	0.0009893	46.56
	70	*k*=0.0119, *a*=1.0837	0.9908	0.2267795	0.1082357	90.06
5	50	*k*=0.0038, *a*=1.2414, *c*=-0.2220	0.9998	0.0000416	0.0000204	4.783
	60	*k*=0.0044, *a*=1.3496, *c*=-0.3388	0.9998	0.0000412	0.0000200	4.318
	70	*k*=0.0064, *a*=1.3957, *c*=-0.3749	0.9997	0.0000847	0.0000404	5.092
6	50	*k*=0.0059, *ko*=0.0059, *a*=0.5646, *b*=0.5120	0.9938	0.0014071	0.0006886	44.05
	60	*k*=0.0079, *ko*=0.0079, *a*=0.5637, *b*=0.5124	0.9918	0.0020404	0.0009893	46.56
	70	*k*=0.0119, *ko*=0.0119, *a*=0.5691, *b*=0.5146	0.9908	0.0024413	0.0011652	35.34
7	50	*k*=0.0054, *a*=1.0000	0.9910	0.0020491	0.0010027	54.81
	60	*k*=0.0106, *a*=1.8387	0.9972	0.0007004	0.0003396	28.33
	70	*k*=0.0162, *a*=1.8884	0.9974	0.0006883	0.0003285	19.75
8	50	*k*=0.0085, *a*=6.7845E-11, *b*=0.6464	0.9910	0.0419776	0.0205422	226.68
	60	*k*=0.0112, *a*=4.6417E-11, *b*=0.6584	0.9890	0.0404951	0.0196339	200.89
	70	*k*=0.0165, *a*=5.1253E-11, *b*=0.6646	0.9874	0.0033528	0.0016002	41.78
9	50	*k*=0.0059, *a*=0.1895, *b*=0.4447, *c*=0.4425, *g*=0.0059, *h*=0.0059	0.9938	0.0014071	0.0006886	44.05
	60	*k*=0.0081, *a*=0.1743, *b*=0.4544, *c*=0.4476, *g*=0.0079, *h*=0.0079	0.9918	0.0020409	0.0009895	46.04
	70	*k*=0.0118, *a*=0.1643, *b*=0.4805, *c*=0.4387, *g*=0.0119, *h*=0.0119	0.9908	0.0024407	0.0011648	35.47

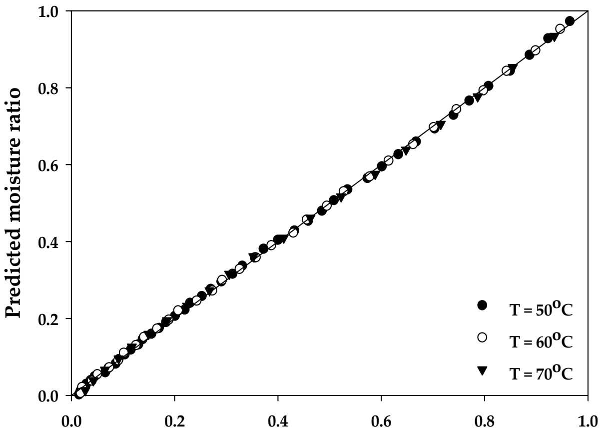

Fig. 3. Comparison of experimental and calculated dimensionless moisture ratio values by the Logarithmic model.

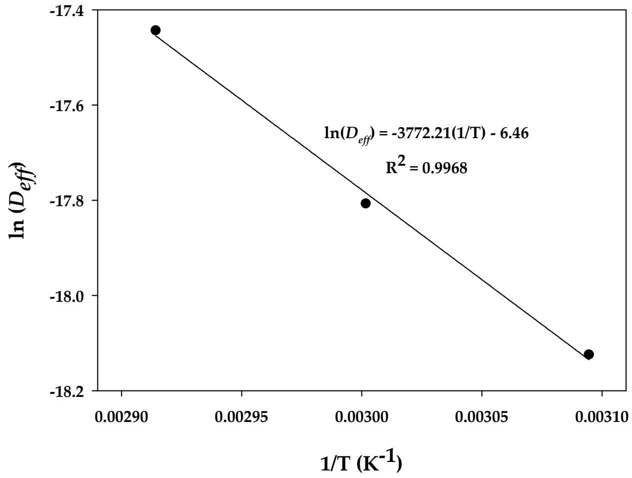

Fig. 4. Arrhenius-type relationship between the effective diffusivity and absolute temperature.

ture ratio values, which is given by a 45° straight line. The Logarithmic model was also suggested by others to describe hot-air drying of single apricot (25), olive cake (34), organic apple slices (35), apple pomace (28), pumpkin slices (27), and strawberry (36).

Effective diffusivity and activation energy

It was shown that internal mass transfer resistance controls the drying time as indicated by the presence of a falling rate drying period. Thus, the values of D_{eff} at different drying temperatures could be attained by using Eq. (9). The values of D_{eff} for the runs were 1.345×10^{-8}, 1.848×10^{-8}, and 2.658×10^{-8} m^2/s at 50, 60, and 70°C, respectively. The values of D_{eff} increased with increases in the drying air temperature. Additionally, these values are comparable to $1.047 \sim 3.685 \times 10^{-8}$ m^2/s for fresh apple pomace dried at different microwave output powers (37), $2.992 \sim 9.154 \times 10^{-8}$ m^2/s for pre-treated apple pomace dried at different microwave output powers (37), and $6.03 \times 10^{-9} \sim 3.15 \times 10^{-8}$ m^2/s for vegetable wastes dried in the temperature range of 50～150°C (38). Nevertheless, the values for D_{eff} obtained from this study were greater than those of $2.51 \sim 3.23 \times 10^{-11}$ m^2/s reported by Pathare and Sharma (2) for infrared convective drying of onion slices at air temperature in the range of 35～45°C probably due to different heating mechanism being applied to the onion sample.

The natural logarithm of D_{eff} as a function of the reciprocal of absolute temperature was plotted in Fig. 4. The activation energy (E_a) was calculated from the slope of the plot showing a linear relationship derived from the Arrhenius-type equation. The values of activation energy can be found to be 31.36 kJ/mol. The value obtained in this study is in the range of 15～40 kJ/mol for various foods reported by Rizvi (39). The E_a of onion slices is little higher than that of *Agaricus bisporus* and *Pleurotus florida* mushrooms (19.79 and 23.59 kJ/mol) (40), red chillies (24.47 kJ/mol) (41), apple slices (19.96～22.62 kJ/mol) (42), and Uryani plum (24.83 kJ/mol) (43), and similar to that of green beans (35.43 kJ/mol) (44), but lower than that of okra (51.26 kJ/mol) (45), and green pepper (51.4 kJ/mol) (46).

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