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RESEARCH NOTE

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Modeling for Vacuum Drying Characteristics of Onion Slices

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Abstract In this study, drying kinetics of onion slices was examined in a laboratory scale vacuum dryer at an air temperature in a range of 50-70°C. Moisture transfer from onion slices was described by applying the Fick's diffusion model, and the effective diffusivity was calculated. Temperature dependency of the effective diffusivity during drying process obeyed the Arrhenius relationship. Effective diffusivity increased with increasing temperature and the activation energy for the onion slices was estimated to be 16.92 kJ/mol. The experimental drying data were used to fit 9 drying models, and drying rate constants and coefficients of models tested were determined by non-linear regression analysis. Estimations by the Page and Two-term exponential models were in good agreement with the experimental data obtained.

Keywords: drying, vacuum, kinetics, onion, thin-layer, model

Introduction

Onion (*Allium cepa* L.) is considered as one of the most important and widely consumed crops in many countries (1) and its production ranked the third in the world among 7 major vegetables, namely onion, garlic, cauliflower, green peas, cabbage, tomato, and green beans (2). Onion has long been used as both spice and food during processing and cooking because of its distinctive flavor and taste (3). The consumption of onion has been increasing significantly partly due to its health promoting properties and flavor (4). Onion is semi-perishable and has a short storage life. One of the simplest ways to improve the shelf-life of fruits and vegetables is to reduce the moisture content (i.e., drying) (5). Drying provides a longer shelf-life to the food, cheaper transportation cost, and smaller space demand during storage (6). The dried onion has become a standard ingredient in a wide variety of processed foods as flavor additive (7) and the uses of dried onions have increased in mass (8).

The conventional air-drying is the most frequently used drying operation in the food and chemical industries; however, vacuum drying provides an alternative to the conventional atmospheric drying with some advantages. In vacuum drying, moisture from food is removed under low pressure and the operation has some distinctive characteristics such as a higher drying rate, lower drying temperature, and an oxygen deficient processing environment (9). In addition, the oxidative degradation such as oxidation of fat and browning can be minimized since the moisture removal takes place in the absence of oxygen (10).

A sound knowledge of the drying kinetics of onion and an adequate simulation model are required to design, optimize, and control the drying processes, which are important steps in food processing industry. Albeit several studies have been carried out to investigate the drying behavior of onion by infrared radiation (8,11-13) and hot-air (14,15), systematic modeling of vacuum drying behavior of onion slices is still lacking for engineering design.

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 (64±0.5 mm diameter, 6.0±0.05 mm thick) 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. Samples (3 slices) were immediately weighed and placed into a vacuum dryer (VOS-301SD; Tokyo Rikakikai Co., Tokyo, Japan) without any pre-treatments. The average weight of the sample used was about 69±1 g. The initial moisture content of the onion samples was determined by vacuum drying at 70°C for 24 hr (16). The initial moisture content of the slices was 1,224% (d.b.).

Drying experiment The sliced onions were dried at air temperature of 50, 60, and 70°C in a vacuum dryer after the dryer reached steady state conditions. Slices were spread in a single layer on the tray and the absolute pressure in the dryer was 0.1 mPa. Moisture losses of samples were recorded at 30 min intervals for 540-1,020 min depending on the air temperature. The weight of samples collected during each drying test was converted into moisture content in dry basis. It was considered that dry product obtained equilibrium condition with the atmosphere inside the drying chamber when constant weight at 3 consecutive times was attained. That moisture content was considered as equilibrium moisture content at each drying temperature. Each experiment was replicated 3 times and the average

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values were used for analysis. The moisture content of dry sample was determined by vacuum drying at 70°C for 24 hr (17).

Drying modeling The moisture ratio (MR) and drying rate of onion slices during the thin layer drying experiments were calculated using the following equations:

$$MR=\frac{M-M_e}{M_o-M_e} \tag{1}$$

$$Drying\ rate=\frac{M_{t+dt}-M_t}{dt} \tag{2}$$

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, t is drying time (min).

Empirical models: Nine well-known thin layer drying models in Table 1 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 Levenberg-Marquardt procedure in 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, 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:

$$RMSE=\left[\frac{1}{N}\Sigma_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2\right]^{1/2} \tag{3}$$

$$\chi^2=\frac{\Sigma_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2}{N-z} \tag{4}$$

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 constant in model. The model was considered best when RMSE at a minimum value, χ^2 at a minimum value, and R^2 at a maximum value were obtained.

Diffusion model: Fick's second law of unsteady state diffusion given in Eq. 5 can be used to determine the moisture ratio in Eq. 6. The solution of Fick's second law in slab geometry, with the assumptions of moisture migration being by diffusion, negligible shrinkage, and constant diffusivity can be simplified to Eq. 6 for long drying periods (17):

$$\frac{\partial M}{\partial t}=\nabla[D_{eff}(\nabla M)] \tag{5}$$

$$MR=\frac{M-M_e}{M_o-M_e}=\frac{8}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}t}{4L^2}\right) \tag{6}$$

where, D_{eff} is the effective moisture diffusivity (m²/sec), L the half thickness of slab (m) (1,8). 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.

The effective moisture diffusivity can be related with temperature by simple Arrhenius-type relationship:

$$D_{eff}=D_o\exp\left(-\frac{E_a}{RT}\right) \tag{7}$$

where, D_0 the pre-exponential factor of Arrhenius equation (m²/sec), 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

Drying kinetics of onion slices Drying of the onion slices started with an initial moisture content around 1,214% (d.b.) and continued until a constant weight at 3 consecutive reading was attained, e.g., to the final moisture content of around 17.69-19.14% (d.b.) which was then considered as the equilibrium moisture content for further analysis. Curves of moisture ratio versus drying time for the different drying air temperatures are shown in Fig. 1. The moisture ratio of onion slices reduced exponentially with the drying time evidently, which are typical to ones for food stuffs (8). The air temperature had a significant influence on the moisture ratio of samples. As the air temperature increased, the drying curves became steeper inducing higher moisture removal thus resulted in substantial decrease in drying time.

Drying rates of the onion slices was calculated using Eq. 2. The changes in the drying rates versus moisture content are shown in Fig. 2. It is apparent that drying rate decreases continuously with drying time. 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 (18) and shows the diffusion-dominant drying phenomena. At the beginning of drying process, drying rate was very high, and drying rate continued to decrease as moisture content approached to equilibrium moisture content. Similar results have been presented for onion slices (1,15), red chillies (18), aromatic plants (19), single apricot (20), mushrooms (21), and red pepper (22).

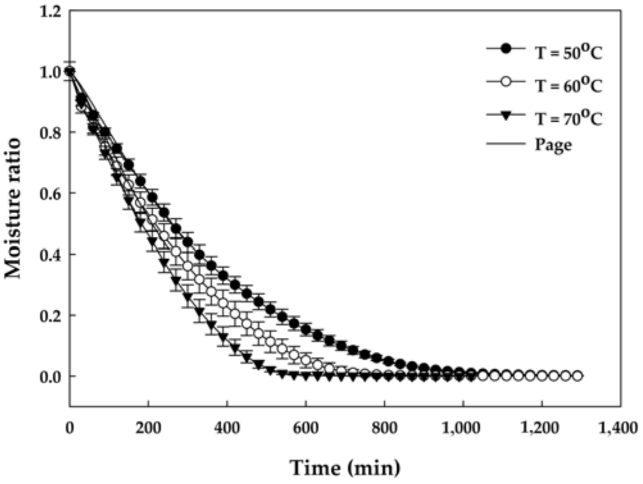

Fig. 1. Thin layer vacuum drying curves for onion slices at different air temperatures.

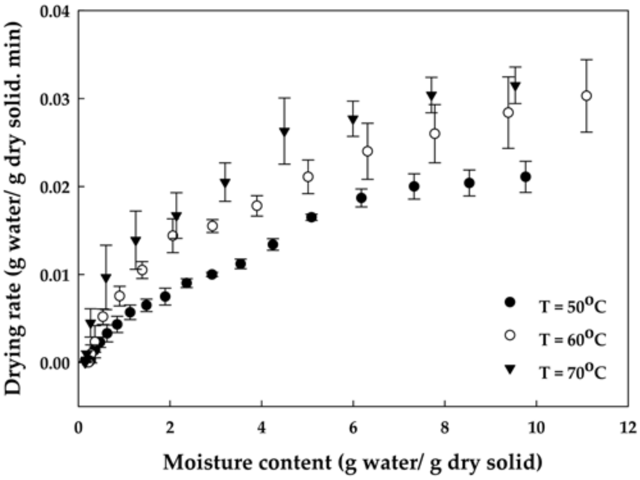

Fig. 2. Variation of drying rate with moisture content.

The drying rate increased with increase in air temperature. The drying rate was more for onion slices dried at higher temperature than the onion slices dried at lower temperature for the same average moisture content of the onions. Due to the fact that the relative humidity of the drying air at higher temperature was less compared to that at lower temperature, the difference in the partial vapor pressure between onions and the surrounding was more for higher temperature drying environment (18). This resulted in higher moisture transfer rate with higher temperature drying air.

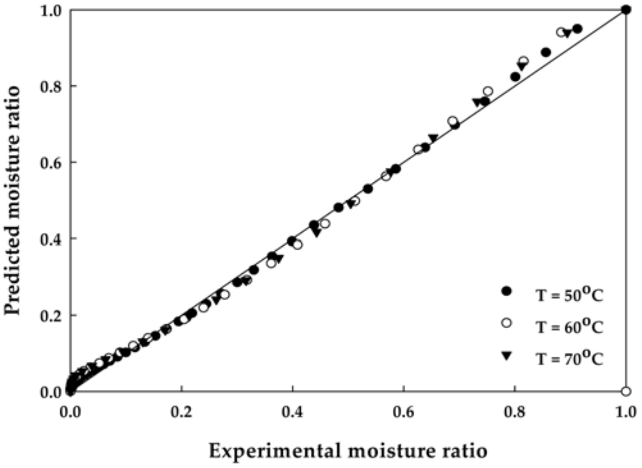

Fig. 3. Comparison of experimental and calculated dimensionless moisture ratio values by the Page model.

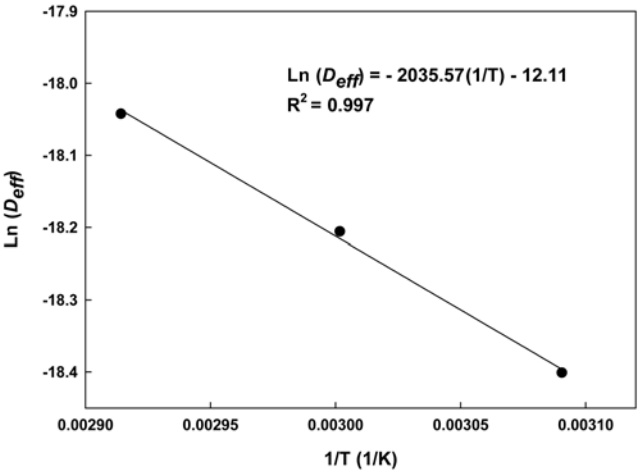

Fig. 4. Arrhenius-type relationship between the effective diffusivity and absolute temperature.

Model evaluation The average moisture ratio of onion slices at various drying air temperatures viz., 50, 60, and 70 °C (Fig. 1) was fitted in selected thin layer drying models in Table 1. The values of coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE) with estimated parameters for proposed models are presented in Table 2. Based on the criteria of the highest R^2 and the lowest RMSE and, 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 higher R^2 values and the lower RMSE and values were obtained from the Page and Two-term exponential models. The R^2, RMSE, and χ^2 values of Page and Two-term exponential models vary between 0.9838-0.9988, 0.000113-0.000220, and 0.000230-0.000449 and 0.9958-0.9986, 0.000075-0.000279, and 0.000154-0.000574, respectively. According to these results, Page and Two-term exponential models may be considered the best models in present study to represent the vacuum drying behavior of onion slices within the experimental range of study. Figure 3 compares experimental and predicted moisture ratios with the Page model versus drying time for dried onion slices at 50, 60, and 70°C. The Page model was also suggested by others to

Table 1. Selected drying models for describing onion drying data

No.	Model name	Model
1	Newton	$MR=\exp(-kt)$
2	Page	$MR=\exp(-kt^n)$
3	Modified Page	$MR=\exp((-kt)^{\mathrm{n}})$
4	Henderson and Pabis	$MR=a\exp(-kt)$
5	Logarithmic	$MR=a\exp(-kt)+c$
6	Two-term	$MR=a\exp(-kt)+b\exp(-k_0t)$
7	Two-term exponential	$MR=a\exp(-kt)+(1-a)\exp(-kat)$
8	Approximation of diffusion	$MR=a\exp(-kt)+(1-a)\exp(-kbt)$
9	Modified Henderson and Pabis	$MR=a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$

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
1	50	k=0.0031	0.9929	0.000799	0.000393
	60	k=0.0038	0.9888	0.001199	0.000588
	70	k=0.0046	0.9838	0.002208	0.001072
2	50	k=0.0008, n=1.2098	0.9988	0.000230	0.000113
	60	k=0.0009, n=1.2537	0.9967	0.000449	0.000220
	70	k=0.0006, n=1.3622	0.9838	0.000381	0.000185
3	50	k=0.0028, n=1.0586	0.9929	0.000801	0.000394
	60	k=0.0035, n=1.0846	0.9888	0.001198	0.000587
	70	k=0.0042, n=1.0996	0.9838	0.002208	0.001073
4	50	k=0.0031, a=1.0556	0.9945	0.000622	0.000306
	60	k=0.0039, a=1.0540	0.9904	0.001031	0.000505
	70	k=0.0049, a=1.0801	0.9872	0.001742	0.000846
5	50	k=0.0029, a=1.0672, c=-0.0295	0.9970	0.000353	0.000174
	60	k=0.0036, a=1.0672, c=-0.0298	0.9934	0.000701	0.000344
	70	k=0.0043, a=1.1065, c=-0.0498	0.9922	0.001066	0.000578
6	50	k=0.0031, $k_{0=}$0.0031, a=0.5505, b=0.5051	0.9945	0.000622	0.000306
	60	k=0.0039, $k_{0=}$0.0039, a=0.5532, b=0.5008	0.9904	0.001031	0.000505
	70	k=0.0049, $k_{0=}$0.0049, a=0.5742, b=0.5059	0.9872	0.001742	0.000846
7	50	k=0.0040, a=1.7389	0.9986	0.000154	0.000075
	60	k=0.0051, a=1.7689	0.9962	0.000405	0.000198
	70	k=0.0066, a=1.8728	0.9958	0.000574	0.000279
8	50	k=0.0048, a=4.9357E-001, b=0.6160	0.9929	0.000803	0.000395
	60	k=0.0058, a=5.9558E-011, b=0.6501	0.9888	0.001194	0.000581
	70	k=0.0068, a=3.3355E-008, b=0.6807	0.9838	0.002210	0.009073
9	50	k=0.0031, a=0.3639, b=0.3575, c=0.3342, g=0.0031, h=0.0031	0.9945	0.000622	0.000306
	60	k=0.0039, a=0.3656, b=0.3567, c=0.3317, g=0.0039, h=0.0039	0.9904	0.001031	0.000505
	70	k=0.0049, a=0.3800, b=0.3647, c=0.3354, g=0.0049, h=0.0049	0.9872	0.001742	0.008460

Table 3. Values of effective diffusivity attained at various air temperatures

Air temperature (°C)	Effective diffusivity (m^2/sec)
50	1.02×10^{-8}
60	1.24×10^{-8}
70	1.46×10^{-8}

describe thin layer drying of carrots (23), okra (24), pears (25), kiwi fruit (26), and green bell pepper (27). It can be seen that there was a good conformity between experimental and predicted values.

Moisture diffusivity The estimated values of D_{eff} for different temperatures are presented in Table 3. The diffusivity values were 1.02×10^{-8}, 1.24×10^{-8}, and 1.46×10^{-8} m^2/sec at 50, 60, and 70°C, respectively. The values of D_{eff} increased progressively as drying air temperature increased. This reduced the drying time considerably. The values for D_{eff} obtained from this study are comparable to 1.345-2.658×10^{-8} m^2/sec for onion slices dried in a hot-air dryer (28) and 1.047-3.685×10^{-8} m^2/sec for fresh apple pomace dried at different microwave output powers (29). Nevertheless, the values for D_{eff} obtained from this study were greater than those of 2.51-3.23×10^{-11} m^2/sec reported by Pathare and Sharma (1) 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.

Activation energy The activation energy (E_a) for diffusion was calculated from the slope of the plot on ln(D_{eff}) versus $1/T$ in Fig. 4. It was found to be 16.92 kJ/mol. The value obtained in this study is in the range of 15-40 kJ/mol for various foods reported by Rizvi (30) and similar value to those proposed in the literature for the drying of different foods: 15.77 kJ/mol for sludge of olive oil extraction (31), 17.54 kJ/mol for unbalanced leek samples with 2 cm thickness (32), 17.97 kJ/mol for olive cake (23), 19.27 kJ/mol for industrial grape by-products (33), 19.96-22.62 kJ/mol for red delicious apple slices (34), respectively.

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