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MODELING OF MASS TRANSFER PERFORMANCE OF HOT-AIR DRYING OF SWEET POTATO (*Ipomoea batatas* L.) SLICES

Article Highlights

- The sweet potato slices are forced convection dried by hot air in tunnel dryer
- The drying models are investigated at different conditions
- The effective diffusivities and activation energy are estimated

Abstract

In order to investigate the transfer characteristics of the sweet potato drying process, a laboratory convective hot air dryer was applied to study the effects of drying temperature, hot air velocity and thickness of sweet potato slice on the drying process. The experimental data of moisture ratio of sweet potato slices were fitted with mathematical models, and the effective diffusion coefficients were calculated. The results showed that temperature, velocity and thickness influenced the drying process significantly. The Logarithmic Model showed the best fit to experimental drying data for temperature and the Wang and Singh model was found to be the most satisfactory for velocity and thickness. It was also found that, with the increase of temperature from 60 to 80 °C, the effective moisture diffusion coefficient varied from 2.962×10^{-10} *to* 4.694×10^{-10} m^2 s^{-1}*, and it fitted the Arrhenius equation, the activation energy was 23.29 kJ* mol^{-1}*; with the increase of hot air velocity from 0.423 to 1.120 m* s^{-1}*, the values of effective moisture diffusion coefficient varied from* 2.877×10^{-10} *to* 3.760×10^{-10} m^2 s^{-1}*; with the increase of thickness of sweet potato slice from 0.002 to 0.004 m, the values of effective moisture diffusion coefficient varied from* 3.887×10^{-10} *to* 1.225×10^{-9} m^2 s^{-1}*.*

Keywords: sweet potato, hot air drying, models, effective diffusion coefficient, activation energy.

Sweet potato (*Ipomoea batatas* Lam.) is grown throughout the tropics and subtropics. The major producers include China, Indonesia, Nigeria, Uganda and Viet Nam. Sweet potatoes are excellent sources of vitamin A and C, and starch. Moreover, they are high in energy and dietary fiber, low in fat, and are important sources of beta-carotene [1]. Fresh sweet potatoes are highly perishable due to their high moisture content and the seasonal nature of their production, so in some countries they are processed into various products by drying.

Drying is probably the oldest and the most important method of food preservation practiced by humans. Development of drying technologies has been important for food and agro-products, especially over the past two decades [2]. Dehydration improves food stability, since it can considerably reduce the water content and microbiological activity of the material, as well as minimize physical and chemical changes during its storage [3], reduce spoilage, increase shelf life, reduce the product's mass and give added value as it is without chemical treatments.

The most important aspect of drying technology is the mathematical model of the drying processes and equipment [4]. Knowledge of the drying kinetics of biological materials is essential to the design, optimization and control of drying process [5]. The principle of modeling is based on having a set of mathematical equations that can adequately charac-

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terize the system. In particular, the solution of these equations must allow prediction of the process parameters as a function of time at any point in the dryer based only on the initial conditions [6]. Many mathematical models have proposed to describe the drying process, of them, thin-layer drying models have been widely in use [7]. Recently, there have been many studies on the mathematical modeling and experimental studies of the drying characteristics of various vegetables and fruits, such as parsley leaves [4], organic tomato [5], bay leaves [6], golden apples [8], banana [9], berberis [10], Asian white radish [11], pea [12], grape [13] and tomato [14]. There are a limited number of reported studies on drying kinetics of sweet potato. Diamante and Munro [15] studied the effect of air temperature, velocity and humidity and slice thickness of sweet potato slices. They reported that the modified Page model best described the drying behaviour of sweet potato. Singh *et al.* [16] studied the effect of air temperature and pretreatments (potassium metabisulphite and citric acid solutions) on drying kinetics of sweet potato slices. They found that the drying process took place in the falling rate period and the Page model was found to describe well the drying characteristics. Doymaz [17] studied the effective moisture diffusivity and activation energy of sweet potato in thin-layer drying at different temperature using a cabinet dryer. However, no studies on effective moisture diffusivity of sweet potato in thin-layer convection drying at different hot air velocities and thicknesses of sweet potato slices have yet been reported.

The aim of this study was to investigate the effect of drying temperature, velocity and thickness on the drying time during hot air forced convection drying in tunnel dryer. Furthermore, the drying kinetics were also investigated. A semi-theoretical model was developed to describe the drying kinetics of the samples through fitting the experimental data to six mathematical models available in the literature. The effective moisture diffusivities and activation energy of the sweet potato slices samples were estimated from Fick’s second law and the Arrhenius equation.

MATERIALS AND METHODS

Material

Sweet potatoes were purchased from a local farmer markets, in Hangzhou, China. The samples were stored in a refrigerator at 4 °C until used. The sweet potatoes were washed with tap water, peeled and sliced manually (30×20×2 mm^3, 30×20×3 mm^3, and 30×20×4 mm^3). The average initial moisture content of the samples was found as 4.57±0.15 kg water kg^{-1} dry matter.

Experimental apparatus

A digital experiment drying tunnel (model DG100D, Zhejiang science instrument control equipment Co., LTD., China) was used for the drying experiment. The line diagram of the instrumentation is shown in Figure 1. Tunnel dryer basically consists of a centrifugal fan to supply the air-flow, an electric heater and an electronic proportional controller, which controls the hot air temperature and velocity, and shows the mass of drying material. Air volume flow was regulated by valve, air velocity equal to the air flow divided by drying chamber circulation area. The air passed through the heating unit and was heated to the desired temperature and channeled to the drying tunnel. The air temperature was controlled by means of a proportional controller. The flow cross-sectional area of tunnel is 18 cm×18 cm, the hot air flowed horizontal through the tray with holes and superficial area of 10 cm×10 cm. The accuracy of the temperature control system was 0.1 °C, accuracy of the weight control system was 0.1 g, and that of the air volume flow control system was 0.1 m^3 h^{-1}. After drying using equipment above, the material was further dried using an electrical thermostatic drum wind drying oven (model DHG-9123A, Shanghai Jinghong laboratory equipment Co., LTD., China). The initial mass, drying mass and oven-dry mass were determined with precise analytical balance (Model BS124S, Beijing Sartorius instrument system Co., LTD., China). The thickness of sweet potato slices was measured by ruler and the accuracy was 0.0002 m.

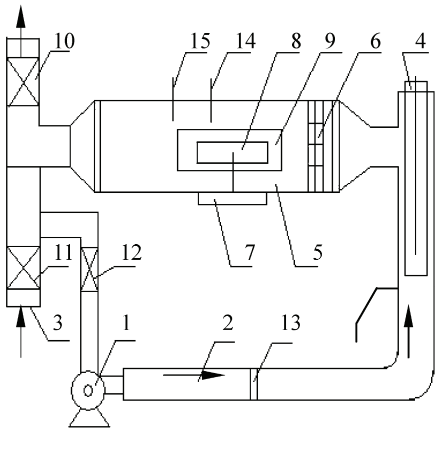

Figure 1. Schematic diagram of drying system. 1) draught fan; 2) pipeline; 3) air intake; 4) heater; 5) tunnel dryer; 6) airflow uniform device; 7) weighing sensor; 8) material tray; 9) sight glass door; 10, 11, 12) butterfly valves; 13) pressure sensor; 14) dry bulb temperature sensor; 15) wet bulb temperature sensor.

Experimental procedure

The experiments were performed at drying temperatures ranging from 60 to 80 °C, in 5 °C increments, air velocity ranging from 0.423 to 1.120 m s^{-1}, the thickness of sweet potato slice ranging from 0.002 to 0.004 m, and relative humidity 10-15%. The relative humidity was determined using wet and dry bulb temperatures of drying air obtained from the existing chart. The temperature and air velocity of drying were set till stabilizing. The mass of sweet potato slice was weighed and 20.5±0.5 g mass of sample was utilized in each experiment. The sample was loaded evenly in drying tray which covered the whole drying area as a thin-layer. The drying tray was put into tunnel dryer. The drying time and mass of the material were recorded. The test was stopped once the mass was invariable. Afterwards, the drying tray was taken out from drying tunnel, put into the oven and dried till a constant mass at 105 °C. The oven-dry mass of sweet potato slice was obtained. All the drying experiments were conducted in triplicate and the average of the moisture content at each value was used for drawing the drying curves.

Mathematical modeling of drying curves

The moisture content of drying sample at time t can be transformed to be moisture ratio (MR):

$$X_t = \frac{m_t - m_g}{m_g} \tag{1}$$

$$MR = \frac{X_t - X^*}{X_0 - X^*} \tag{2}$$

where X_t, m_t and m_g are the moisture content at any time (kg water kg^{-1} dry matter), weight of sample at any time (kg) and absolute dried weight of sample (kg) respectively; MR, X_0 and X^* are moisture ratio (dimensionless), initial moisture content (kg water kg^{-1} dry matter) and equilibrium moisture content (kg water kg^{-1} dry matter), respectively.

The drying rate (DR) of sweet potato slices was calculated using Eq. (3):

$$DR = \frac{X_{t+\mathrm{d}t} - X_t}{\mathrm{d}t} \tag{3}$$

where DR is the drying rate (kg water kg^{-1} dry matter s^{-1}), $X_{t+\mathrm{d}t}$ is the moisture content at $t + \mathrm{d}t$ (kg water kg^{-1} dry matter), t is time (s), $\mathrm{d}t$ is time increment (s).

The drying data obtained were fitted to six thin-layer drying models detailed in Table 1 using the non-linear least squares regression analysis. Regression analysis was performed using DataFit software (Oakdale Engineering). The coefficient of determination (R^2) was the primary criterion for selecting the best equation to describe the drying curve. In addition, the reduced chi square (χ^2) as the mean square of the deviations between the experimental and predicted values for the models and the root mean square error analysis ($RMSE$) and the mean relative percent error (P) were used to determine the goodness of fit. The higher the values of R^2, the lower were the values of χ^2 and $RMSE$ and P, and hence was better goodness of fit [6,8,13,18-20]. These parameters can be calculated as follows:

$$P = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|MR_{\mathrm{exp},i} - MR_{\mathrm{pre},i}\right|}{MR_{\mathrm{exp},i}} \tag{4}$$

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

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\mathrm{pre},i} - MR_{\mathrm{exp},i}\right)^2\right]^{1/2} \tag{6}$$

where $MR_{\mathrm{exp},i}$ is the experimental moisture ratio; $MR_{\mathrm{pre},i}$ is the predicted moisture ratio; N is the number of observations; z is the number of constants.

Table 1. Thin-layer drying models applied to the sweet potato slices drying curves

Model no.	Model name	Model
1	Newton	$MR = \exp(-kt)$
2	Henderson and Pabis	$MR = a\exp(-kt)$
3	Logarithmic	$MR = a\exp(-kt) + c$
4	Page	$MR = \exp(-kt^n)$
5	Modified page	$MR = a\exp(-kt^n)$
6	Wang and Singh	$MR = 1-at+bt^2$

Determination of effective moisture diffusivity

Fick's second law of diffusion equation was used to fit the experimental drying data for the determination of effective moisture diffusivity coefficients.

$$\frac{\partial X}{\partial t} = D_{\mathrm{eff}}\frac{\partial^2 X}{\partial x^2} \tag{7}$$

The solution of diffusion (Eq. (7)) for slab geometry is solved by Crank [21] and supposed uniform initial moisture distribution, negligible external resistance, constant diffusivity and negligible shrinkage:

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(\frac{-(2n-1)^2\pi^2 D_{\mathrm{eff}}t}{4H^2}\right) \tag{8}$$

where D_{eff} is the effective moisture diffusivity (m^2 s^{-1}), t is the drying time (s), H is the half-thickness of samples (m) and n is a positive integer. Only the first term of Eq. (8) can be used for long drying times [22-24].

$$MR = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D_{\text{eff}} t}{4H^2}\right) \quad (9)$$

The slope is determined by plotting ln (MR) against time according to Eq. (9):

$$Slope = \frac{\pi^2 D_{\text{eff}}}{4H^2} \quad (10)$$

Computation of activation energy

The dependence of the effective moisture diffusivity on the temperature is generally described by the Arrhenius equation (Eq. (11)) [25]:

$$D_{\text{eff}} = D_0 \exp\left(\frac{-E_a}{R(T+273.15)}\right) \quad (11)$$

where D_0 is the pre-exponential factor of Arrhenius equation in m^2 s^{-1}, E_a is the activation energy in kJ mol^{-1}, R is the universal gas constant in kJ mol^{-1} K^{-1}, and T is hot air temperature in °C.

RESULTS AND DISCUSSION

Drying characteristics

The variation of moisture ratio with drying time at hot air temperatures of 60, 65, 70, 75 and 80 °C for sweet potato sliced to 0.002 m thickness and at 0.946 m s^{-1} air velocity are shown in Figure 2. An increase in drying air temperature resulted in a decrease in the drying time. Drying rate was estimated based on Eq. (3) and its changes with drying time are as shown in Figure 3. An important influence of air drying temperature on drying rate could be observed in the curves. It shows that drying rate decreases continuously with increase in time. There is almost no

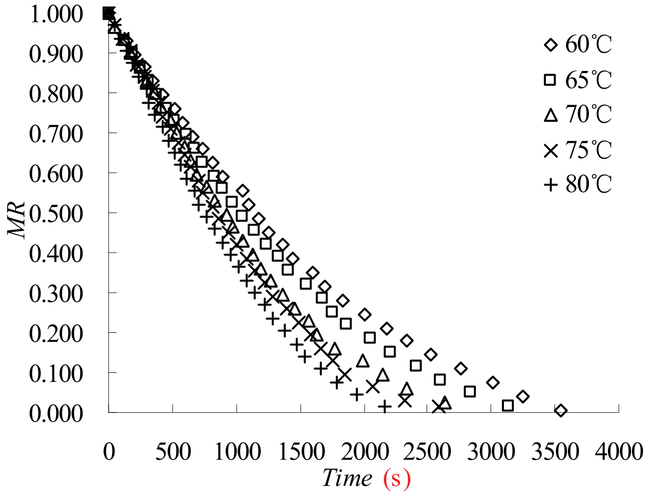

Figure 2. Drying curves for different temperature at velocity 0.946 m s^{-1} and thickness 0.002 m.

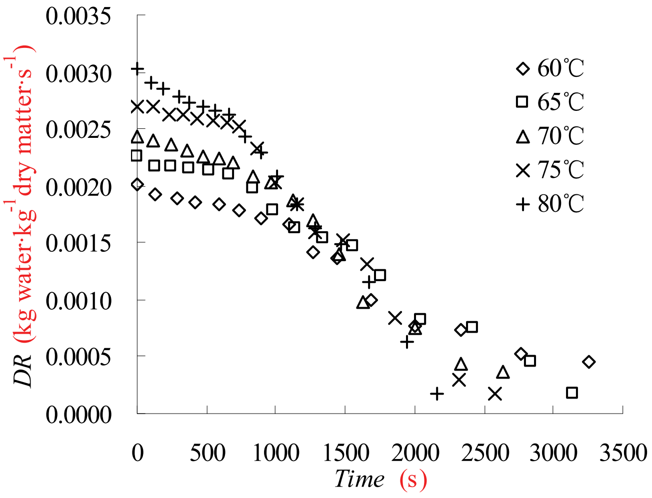

Figure 3. Drying rate curves for different temperature at velocity 0.946 m s^{-1} and thickness 0.002 m.

constant rate of drying period in these curves and the entire drying process occurred in the falling-rate period. These results are in good agreement with the earlier observations of various products [11,16,18,19,25,26].

Moisture removal inside sweet potato slices at 80 °C was higher and faster than at the other investigated temperatures during the time of investigation as the migration to the surface of the moisture and evaporation rate from the surface to air decrease with decrease of the moisture in the product and thus the drying rate clearly decreases. Shorter time of drying was observed at a higher temperature thus increased drying rate. This increase is because of the increased heat transfer potential between the air and the sweet potato slices, which favors the evaporation of water from the sweet potato slices. Similar observations have earlier been reported in the literature [4,11,25].

Figure 4 shows the characteristics drying curves at 70 °C temperature for sweet potato sliced to 0.002 mm thickness and at 0.423, 0.598, 0.733, 0.946 and 1.120 m s^{-1} air velocity. Figure 5 shows the changes in drying rate as a function of drying time at the same air velocity. It is clear that the moisture content and drying rate decrease continuously with drying time. As shown in Figure 5, there was also no constant drying rate period, and the entire drying process occurred in the falling-rate period. The results were generally in agreement with some of the literature on the drying of various food products [27,28].

Moisture removal at 1.120 m s^{-1} was higher and faster than at the other investigated air velocities. Shorter time of drying was observed at higher air velocity, *i.e.*, increased drying rate. This increase is due to the increased convective heat-transfer coefficient and quality transmission coefficient between the air and the sweet potato slices, which favors the evaporation of water from the sweet potato slices. The influence of the drying air velocity is significant at

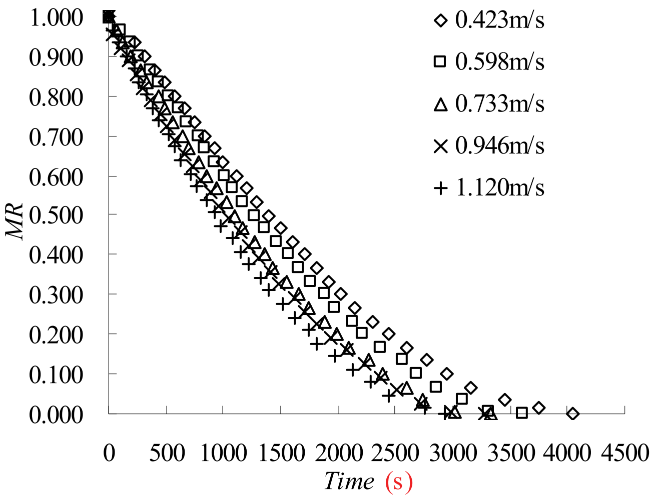

Figure 4. Drying curves for different air velocity at temperature 70 °C and thickness 0.002 m.

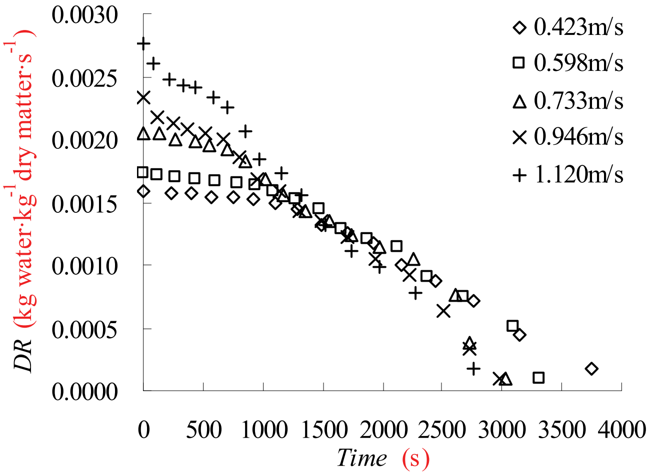

Figure 5. Drying rate curves for different air velocity at temperature 70 °C and thickness 0.002 m.

the beginning of the process, implying that the evaporation initially takes place at the surface, being therefore more directly affected by air velocity. The initial surface evaporation is gradually replaced by an evaporation front that recedes to the interior of the solid. The predominance of air velocity is therefore succeeded by the moisture diffusion process, which becomes the most important factor. The results were generally in agreement with some of the literature on the drying of various food products [27].

Figure 6 shows the characteristics drying curves at 70 °C temperature and 0.946 m s^{-1} air velocity for 0.002, 0.003 and 0.004 mm thickness. Figure 7 shows the changes in drying rate as a function of drying time at the same thickness. The similarly air velocity results are observed. The results were generally in agreement with some of the literature on the drying of various food products [23,24,29,30].

Moisture removal at 0.002 m thickness was higher and faster than the other investigated thickness. Shorter time of drying was observed at a thinner thickness thus increased drying rate. This increase is because of the decreased quality transmission resistance of sweet potato slice, which favors the migration of water from the inside to the surface transmission from the sweet potato slices.

Fitting of drying curves

The drying data obtained from the experiments were fitted by six thin-layer drying models mentioned in Table 1. Non-linear regression analysis was used to estimate the parameters of those six models. The model equations and the statistical results from models for temperature, air velocity and thickness are summarized in Tables 2-4, respectively. The best model describing the thin-layer drying characteristics of sweet potato slices was chosen as the one with the

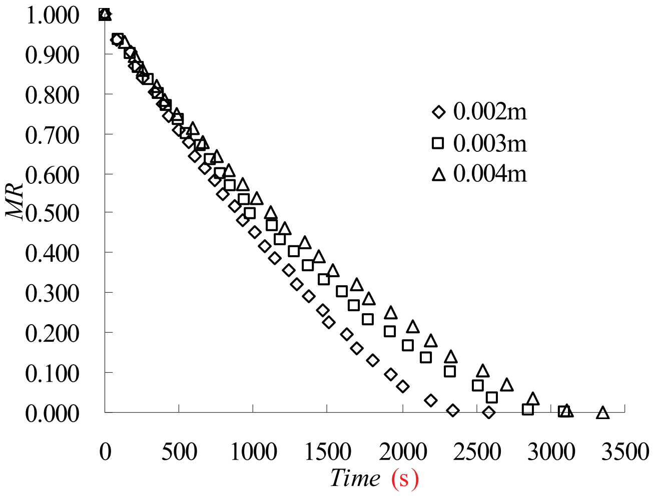

Figure 6. Drying curves for different thickness at temperature 70 °C and velocity 0.946 m s^{-1}.

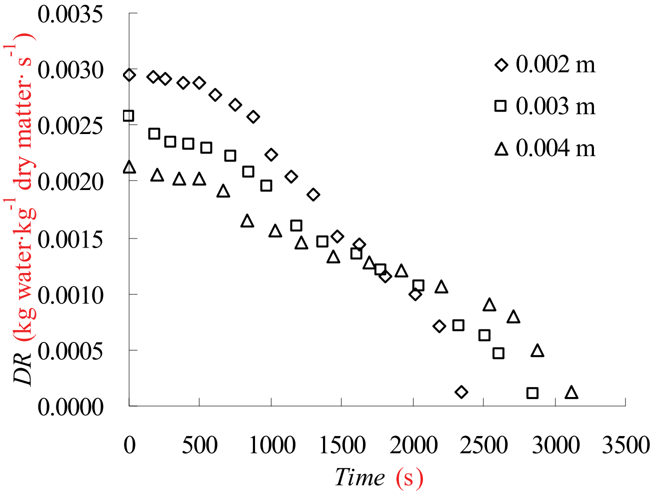

Figure 7. Drying rate curves for different thickness at temperature 70 °C and velocity 0.946 m s^{-1}.

Table 2. The fitting models and statistical results of models at different drying temperatures

Model no.	Temperature, °C	Models	R^2	P	χ^2	$RMSE$
1	60	$MR = \exp(-0.0006693t)$	0.9812	5.6456	0.001169	0.033466
	65	$MR = \exp(-0.0007398t)$	0.9769	6.0454	0.001241	0.034482
	70	$MR = \exp(-0.0008599t)$	0.9651	7.3517	0.002033	0.044183
	75	$MR = \exp(-0.0009344t)$	0.9617	8.4961	0.002597	0.050006
	80	$MR = \exp(-0.0010328t)$	0.9660	7.3478	0.002124	0.045225
2	60	$MR = 1.0925\exp(-0.0007304t)$	0.9909	3.8164	0.000963	0.029710
	65	$MR = 1.0964\exp(-0.0008112t)$	0.9876	4.5659	0.001084	0.031518
	70	$MR = 1.1170\exp(-0.0009645t)$	0.9814	5.2316	0.001755	0.040183
	75	$MR = 1.1411\exp(-0.0010596t)$	0.9810	5.9112	0.002499	0.045630
	80	$MR = 1.1227\exp(-0.0011570t)$	0.9821	5.6201	0.001909	0.042046
3	60	$MR = 1.7266\exp(-0.0002813t)-0.7424$	0.9962	2.9148	0.000193	0.013001
	65	$MR = 1.7216\exp(-0.0003186t)-0.7307$	0.9989	1.3826	0.000058	0.007131
	70	$MR = 1.7695\exp(-0.0003821t)-0.7530$	0.9992	1.0832	0.000064	0.007530
	75	$MR = 1.8209\exp(-0.0003868t)-0.8067$	0.9985	1.8783	0.000103	0.009563
	80	$MR = 4.5894\exp(-0.0001506t)-0.8736$	0.9990	1.4503	0.000062	0.007406
4	60	$MR = \exp(-0.0002500t^{1.1303})$	0.9973	2.5133	0.000162	0.012153
	65	$MR = \exp(-0.0002759t^{1.1323})$	0.9971	2.8165	0.000183	0.012920
	70	$MR = \exp(-0.0002742t^{1.1550})$	0.9923	3.9970	0.000374	0.018519
	75	$MR = \exp(-0.0002598t^{1.1735})$	0.9901	4.4157	0.000378	0.018676
	80	$MR = \exp(-0.0002458t^{1.2027})$	0.9961	2.9701	0.000186	0.013089
5	60	$MR = 0.9488\exp(-0.00002387t^{1.4488})$	0.9877	3.3702	0.000283	0.015674
	65	$MR = 0.9715\exp(-0.00010102t^{1.2692})$	0.9982	1.4990	0.000054	0.006823
	70	$MR = 0.9726\exp(-0.00003105t^{1.4706})$	0.9905	3.0679	0.000246	0.014685
	75	$MR = 0.9789\exp(-0.00006547t^{1.3728})$	0.9996	1.1592	0.000032	0.005321
	80	$MR = 0.9548\exp(-0.00003174t^{1.4976})$	0.9920	2.4123	0.000160	0.011894
6	60	$MR = 1-0.0005120t+6.694\times10^{-8}t^2$	0.9991	1.5123	0.000527	0.02198
	65	$MR = 1-0.0005648t+8.068\times10^{-8}t^2$	0.9997	0.8001	0.000137	0.011197
	70	$MR = 1-0.0006524t+1.058\times10^{-7}t^2$	0.9982	2.2381	0.001214	0.033422
	75	$MR = 1-0.0006897t+1.155\times10^{-7}t^2$	0.9978	2.1226	0.00072	0.025827
	80	$MR = 1-0.0007638t+1.387\times10^{-7}t^2$	0.9991	1.3579	0.000312	0.016987

Table 3. The fitting models and statistical results of models at different hot air velocities

Model no.	Velocity, m s^{-1}	Models	R^2	P	χ^2	$RMSE$
1	0.423	$MR = \exp(-0.0005959t)$	0.9375	11.8852	0.004325	0.064485
	0.598	$MR = \exp(-0.0006506t)$	0.9429	11.3835	0.020180	0.139400
	0.733	$MR = \exp(-0.0007458t)$	0.9553	9.7644	0.002741	0.051373
	0.946	$MR = \exp(-0.0007922t)$	0.9658	8.4937	0.001802	0.041658
	1.120	$MR = \exp(-0.0008502t)$	0.9726	7.1729	0.001527	0.038351
2	0.423	$MR = 1.2205\exp(-0.0007091t)$	0.9708	7.8386	0.003732	0.058691
	0.598	$MR = 1.1913\exp(-0.0007592t)$	0.9706	8.1434	0.003770	0.062669
	0.733	$MR = 1.1468\exp(-0.0008418t)$	0.9734	7.6703	0.002910	0.051906
	0.946	$MR = 1.1095\exp(-0.0008665t)$	0.9763	7.4091	0.002390	0.047039
	1.120	$MR = 1.0995\exp(-0.0009269t)$	0.9825	5.8717	0.001728	0.040001
3	0.423	$MR = 2.0462\exp(-0.0002120t)-1.0199$	0.9989	1.7200	0.000079	0.008346
	0.598	$MR = 3.2753\exp(-0.0001266t)-2.2749$	0.9988	1.6391	0.000808	0.026799
	0.733	$MR = 2.3676\exp(-0.0002062t)-1.3784$	0.9985	2.2554	0.000097	0.009275
	0.946	$MR = 1.6440\exp(-0.0003370t)-0.6625$	0.9995	1.0650	0.000035	0.005600
	1.120	$MR = 1.6836\exp(-0.0003602t)-0.6920$	0.9990	1.9644	0.000101	0.009495

Table 3. Continued

Model no.	Velocity, m s^{-1}	Models	R^2	P	χ^2	$RMSE$
4	0.423	$MR = \exp(-0.00004846t^{1.3287})$	0.9977	3.4176	0.000172	0.012588
	0.598	$MR = \exp(-0.00007797t^{1.2781})$	0.9966	4.2299	0.000273	0.015881
	0.733	$MR = \exp(-0.00021926t^{1.1589})$	0.9939	5.5558	0.000484	0.021135
	0.946	$MR = \exp(-0.00039608t^{1.0872})$	0.9898	6.1569	0.000558	0.022704
	1.120	$MR = \exp(-0.00037243t^{1.1085})$	0.9935	4.3703	0.000334	0.017556
5	0.423	$MR = 0.9830\exp(-0.00002564t^{1.4110})$	0.9987	2.3404	0.000095	0.009125
	0.598	$MR = 0.9824\exp(-0.00002597t^{1.4270})$	0.9957	2.1818	0.000092	0.009025
	0.733	$MR = 0.9816\exp(-0.00007660t^{1.3042})$	0.9954	3.0494	0.000168	0.012178
	0.946	$MR = 0.9721\exp(-0.00017777t^{1.1948})$	0.9964	4.2659	0.000265	0.015311
	1.120	$MR = 0.9706\exp(-0.00013630t^{1.2469})$	0.9989	2.1955	0.000100	0.009386
6	0.423	$MR = 1-0.0004177t+4.000\times10^{-8}t^2$	0.9963	3.7053	0.000344	0.017818
	0.598	$MR = 1-0.0004524t+4.548\times10^{-8}t^2$	0.9972	2.8931	0.000253	0.016228
	0.733	$MR = 1-0.0005332t+6.752\times10^{-8}t^2$	0.9992	1.5019	0.000058	0.007327
	0.946	$MR = 1-0.0005750t+8.147\times10^{-8}t^2$	0.9993	0.9218	0.000073	0.008243
	1.120	$MR = 1-0.0006287t+9.835\times10^{-8}t^2$	0.9997	0.9148	0.000031	0.005335

Table 4. Fitting models and statistical results of models at different thicknesses

Model no.	Thickness, m	Models	R^2	P	χ^2	$RMSE$
1	0.002	$MR = \exp(-0.0009060t)$	0.9795	8.3694	0.002704	0.050953
	0.003	$MR = \exp(-0.0008067t)$	0.9846	7.7777	0.002391	0.047873
	0.004	$MR = \exp(-0.0007312t)$	0.9881	7.4432	0.004974	0.068908
2	0.002	$MR = 1.0512\exp(-0.0009581t)$	0.9836	7.3822	0.002077	0.043716
	0.003	$MR = 1.0403\exp(-0.0008408t)$	0.9870	7.0346	0.001948	0.042254
	0.004	$MR = 1.0296\exp(-0.0007547t)$	0.9895	6.8816	0.004165	0.061531
3	0.002	$MR = 1.9046\exp(-0.0003416t)-0.9315$	0.9990	6.5938	0.001094	0.031727
	0.003	$MR = 1.4709\exp(-0.0004162t)-0.4915$	0.9990	6.9061	0.001236	0.032891
	0.004	$MR = 1.3274\exp(-0.0004387t)-0.3515$	0.9991	7.0720	0.002841	0.049531
4	0.002	$MR = \exp(-0.0003188t^{1.1354})$	0.9897	4.3887	0.000440	0.020073
	0.003	$MR = \exp(-0.0004060t^{1.0793})$	0.9932	3.4801	0.000299	0.016518
	0.004		0.9972	2.7670	0.000187	0.013000
5	0.002	$MR = 0.9589\exp(-0.00005780t^{1.3834})$	0.9972	1.8461	0.000096	0.009156
	0.003	$MR = 0.9653\exp(-0.00011060t^{1.2581})$	0.9989	1.6394	0.000070	0.007801
	0.004	$MR = 0.9798\exp(-0.00017508t^{1.1796})$	0.9984	1.8687	0.000091	0.008848
6	0.002	$MR = 1-0.0006466t+9.520\times10^{-8}t^2$	0.9987	1.1973	0.000058	0.007307
	0.003	$MR = 1-0.0005713t+7.929\times10^{-8}t^2$	0.9994	1.1186	0.000051	0.006851
	0.004	$MR = 1-0.0005189t+6.528\times10^{-8}t^2$	0.9995	1.1598	0.000111	0.010046

highest R^2 values and the lowest P, χ^2 and *RMSE* values. The statistical parameter estimations for temperature showed that R^2, P, χ^2 and *RMSE* values were ranged from 0.9617 to 0.9992, 1.0832 to 8.4961, 0.000032 to 0.002597 and 0.005321 to 0.050006, respectively, and of all the models tested, the R^2 for Logarithmic, Page and Wang and Singh models were all above 0.99, the Logarithmic model gives the higher value of R^2 and the lowest values of P, χ^2 and *RMSE,* hence the Logarithmic model may be selected to represent the thin layer drying behavior of sweet potato slices for temperature. The statistical parameter estimations for air velocity showed that R^2, P, χ^2 and *RMSE* values were ranged from 0.9375 to 0.9998, 0.6988 to 11.8852, 0.000022 to 0.004325 and 0.004541 to 0.139400, respectively, and of all the models tested, the Wang and Singh model gives the highest value of R^2 and the lowest values of P, χ^2 and *RMSE*. The statistical parameter estimations for thickness showed that R^2, P, χ^2 and *RMSE* values were ranged from 0.9795 to 0.9996, 0.8940 to 18.3694, 0.000038 to 0.004974 and 0.005892 to 0.068908, respectively, and of all the models tested, the Wang and Singh model gives also the highest value of R^2 and the lowest values of P, χ^2 and $RMSE$. Therefore the Wang and Singh model may be selected to represent the thin layer drying behavior of sweet potato slices for air velocity and thickness.

Effective moisture diffusivity

The values of effective moisture diffusivity were calculated using Eq. (10) and are shown in Tables 5-7. The $D_{\rm eff}$ values were varied in the range of 2.962×10^{-10} to 4.694×10^{-10} m^2 s^{-1} at 60-80 °C for sweet potato sliced to 0.002 m thickness and at 0.946 m s^{-1} air velocity, in the range of 2.877×10^{-10} to 3.760×10^{-10} m^2 s^{-1} at 0.423-1.120 m s^{-1} of air velocity at 70 °C temperature for sweet potato sliced to 0.002 mm thickness and in the range of 3.887×10^{-10} to 1.225×10^{-9} m^2 s^{-1} at 0.002-004 m of thickness at 70 °C temperature and 0.946 m s^{-1} air velocity, respectively. It was observed that $D_{\rm eff}$ values increased greatly with increasing drying temperature and increasing air velocity and increasing thickness, respectively. When samples were dried at higher temperature, increased heating energy would increase the activity of water molecules leading to higher moisture diffusivity (24). The effective moisture diffusivity relates to moisture concentration except temperature, when samples were dried at higher air velocity, would increase the quality transmission coefficient leading to higher quality transmission rate, the moisture concentration of material surface was accelerated to reduce, the inner moisture of material was promoted to diffuse form inside to outside, and so the $D_{\rm eff}$ was increased. When samples were dried at thinner thickness of sweet potato slice, would decrease the quality transmission resistance leading to higher quality transmission rate. The values of $D_{\rm eff}$ obtained from this study lie within in general range 10^{-12} to 10^{-8} m^2 s^{-1} for drying of food materials [31]. Similar results have been obtained for other agricultural crops like green peas (12], garlic (27] and carrot (29]. The double sample variance and mean t test was carried between the $D_{\rm eff}$ of temperature and thickness, the $|t| = 2.261 < t_{0.05}$ (6) = 2.447, so there is no significant difference between the two average values of $D_{\rm eff}$.

Activation energy

A plot of ln $D_{\rm eff}$ against $1/T$ gave a straight line (R^2 = 0.9870), which is shown in Figure 8. The slope ($-E_a/R$) of the straight line was obtained and by using the Arrhenius relationship, the activation energy was found to be 23.29 kJ mol^{-1}. The value is similar to those proposed in the literature for different fruits and vegetables drying (16.49-20.26 kJ/mol in Asian white radish (11]; 22.48 kJ/mol in green pea (12]).

Table 5. The effective moisture diffusion coefficient at different temperatures

Temperature, °C	$D_{\rm eff}\times10^{-10}$ / m^2 s^{-1}
60	2.9616
65	3.2902
70	3.9150
75	4.3004
80	4.6939

Table 6. The effective moisture diffusion coefficient at different velocities

Velocity, m s^{-1}	$D_{\rm eff}\times10^{-10}$ / m^2 s^{-1}
0.423	3.0220
0.598	3.4524
0.733	3.5892
0.946	3.9446
1.120	4.1089

Table 7. The effective moisture diffusion coefficient of different thicknesses

Thickness, m	$D_{\rm eff}\times10^{-10}$ / m^2 s^{-1}
0.002	3.8870
0.003	7.6750
0.004	12.247

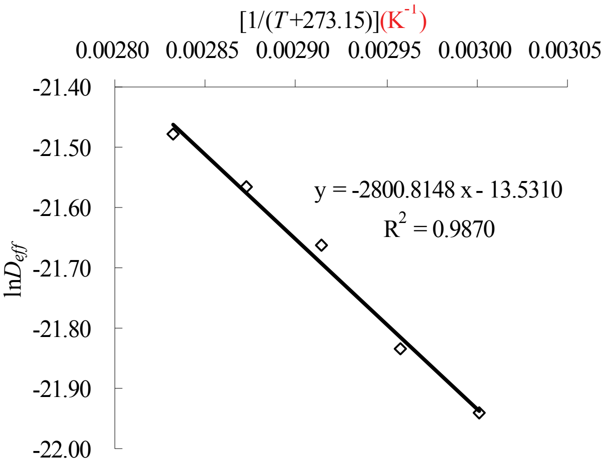

Figure 8. The relationship of ln $D_{\rm eff}$ and $1/T$ at velocity 0.946 m s^{-1} and thickness 0.002 m.

CONCLUSIONS

The effects of drying temperature and hot air velocity and thickness of sweet potato slice on drying characteristics of sweet potato slices were investigated in a forced convective tunnel dryer. Drying occurred in the falling rate period and no constant rate of period of drying was observed. The drying behavior of sweet potato slices was explained by applying six thin layer drying models and goodness of fit was determined using R^2, P, χ^2 and $RMSE$. The results showed that the change of moisture ratio with drying time in the temperature range from 60 to 80 °C can be successfully described by the Logarithmic model (R^2 0.9962-0.9990; P 1.0832-2.9148; χ^2 0.000058-0.000193; $RMSE$ 0.007131-0.013001). The D_{eff} values for drying at 60-80 °C of air temperature and 0.946 m $\mathrm{s^{-1}}$ of air velocity ranged between 2.962×10^{-10} to 4.694×10^{-10} $\mathrm{m^2\ s^{-1}}$. The activation energy for moisture diffusion was found to be 23.29 kJ $\mathrm{mol^{-1}}$. The results also showed that the change of moisture ratio with drying time in the air velocity range from 0.423 to 1.120 m $\mathrm{s^{-1}}$ could be successfully described by the Wang and Singh model (R^2 0.9987--0.9998; P 0.6988-1.8471; χ^2 0.000022-0.000123; $RMSE$ 0.004541-0.010664). The D_{eff} values for drying at 0.423-1.120 m $\mathrm{s^{-1}}$ of air velocity and 70 °C of air temperature ranged between 2.877×10^{-10} to 3.760×10^{-10} $\mathrm{m^2{\cdot}s^{-1}}$; the change of moisture ratio with drying time in the thickness of sweet potato slice ranging from 0.002 to 0.004 m can also be successfully described by the Wang and Singh model (R^2 0.9989-0.9996; P 0.8940-1.1919; χ^2 0.000038--0.000073; $RMSE$ 0.005892-0.008169), the D_{eff} values for drying at 0.002-0.004 m of thickness and 0.946 m $\mathrm{s^{-1}}$ of air velocity and 70 °C of air temperature ranged from 3.887×10^{-10} to 1.225×10^{-9} $\mathrm{m^2\ s^{-1}}$.

Nomenclature

a, b, c	drying coefficients
P	mean relative percent error
D_{eff}	the effective moisture diffusivity, $\mathrm{m^2\ s^{-1}}$
R	the universal gas constant, kJ $\mathrm{mol^{-1}\ K^{-1}}$
D_0	the pre-exponential factor of Arrhenius equation, $\mathrm{m^2{\cdot}s^{-1}}$
R^2	determination of coefficient
DR	drying rate, kg water $\mathrm{kg^{-1}}$ dry matter $\mathrm{s^{-1}}$
$RMSE$	root mean square error
E_a	the activation energy, kJ $\mathrm{mol^{-1}}$
T	drying temperature, °C
H	the half-thickness of samples, m
t	drying time, s
k	drying coefficient
u	air velocity, m $\mathrm{s^{-1}}$
m_g	absolute dried weight of sample, kg
X^*	equilibrium moisture content, kg water $\mathrm{kg^{-1}}$ dry matter
m_t	weight of sample at any time, kg
X_0	initial moisture content, kg water $\mathrm{kg^{-1}}$ dry matter
MR	moisture ratio, dimensionless
X_t	moisture content at any time, kg water $\mathrm{kg^{-1}}$ dry matter
$MR_{\mathrm{exp},i}$	experimental moisture ratio
X_{t+dt}	moisture content at t + dt, kg water $\mathrm{kg^{-1}}$ dry matter
$MR_{\mathrm{pre},i}$	predicted moisture ratio
z	number of coefficients and constants
N	number of observations
χ^2	reduced Chi-square
n	constant, positive integer

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NAUČNI RAD

MODELOVANJE PRENOSA MASE PRI SUŠENJU KRIŠKI SLATKOG KROMPIRA (*Ipomoea batatas* L.) TOPLIM VAZDUHOM

Karakteristike prenosa mase pri sušenju kriški slatkog krompira ispitivane su u laboratorijskoj konvektivnoj sušari. Ispitivan je uticaj temperature sušenja, brzine strujanja toplog vazduha i debljine kriški slatkog krompira na process sušenja. Eksperimentalni podaci o sadržaju vlage kriški slatkog krompira iskorišćeni su za proveru matematičkih modela i izračunavanje vrednosti efektivnog koeficijenta difuzije. Dobijeni rezultati pokazuju da temperatura, brzina strujanja i debljina kriški utiču značajno na process sušenja. Logaritamski model najbolje fituje eksperimentalne podatke u funkciji temperature, a Wang-Singh model u funkciji brzine strujanja i debljine kriški. Utvrđeno je, takođe, da u opsegu temperature od 60 do 80 °C efektivni koeficijent difuzije vlage varira od $2,962\times10^{-10}$ *do* $4,694\times10^{-10}$ $m^2\cdot s^{-1}$ *i da se menja sa temperaturom u skladu sa Areniusovom jednačinom sa vrednošću energije aktivacije 23,29* $kJ\cdot mol^{-1}$. *Sa povećanjem brzine strujanja vazduha od 0,423 do 1,120* $m\cdot s^{-1}$ *efektivni koeficijent difuzije vlage varira od* $2,877\times10^{-10}$ *do* $3,760\times10^{-10}$ $m^2\cdot s^{-1}$, *dok se povećanjem debljine kriški od 2 do 4 mm, on menja od* $3,887\times10^{-10}$ *do* $1,225\times10^{-9}$ $m^2\cdot s^{-1}$.

Ključne reči: slatki krompir, sušenje toplim vazduhom, efektivni koeficijent difuzije, energija aktivacije.