https://doi.org/10.17221/258/2017-CJFS

Pulsed Air Jet Impingement Drying Characteristics of Winter Jujube Slices

*Shi-Yu WEI[1], Gao WANG[2], Yong HUANG[1], Rong-Guang ZHU[1], Qiang WANG[1], Xiang-Nan ZHANG[1], Yu-Xue CAO[1] and Xue-Dong YAO[1]**

[1]College of Mechanical and Electrical Engineering, Shihezi University, Shihezi, [2]Institute of Agricultural Engineering, Anhui Academy of Agricultural Sciences, Hefei; P.R. China

**Corresponding author:yaoxuedong@126.com*

Abstract

Wei S-Y., Wang G., Huang Y., Zhu R-G., Wang Q., Zhang X-N., Cao Y-X., Yao X-D. (2018): Pulsed air jet impingement drying characteristics of winter jujube slices. Czech J. Food Sci., 36: 329–337.

The drying curves, moisture effective diffusivity and drying activation energy of winter jujube slices were here investigated at different drying temperatures (55, 60, 65, 70, 75, and 80°C), wind speeds (6, 7, 8, 9, and 10 m/s) and pulsation rates (rotatational speed of material disk: 4, 5.5, and 7 rpm) in a single-factor experiment design. A mathematical model of pulsed air-jet impingement drying for winter jujube slices was fitted and verified. The results showed that the entire drying process could be described as falling rate drying; the moisture effective diffusivity was in the range 1.52–4.93 × 10^{-9} m^2/s and increased with increasing drying temperature, wind speed and pulsation rate. The drying activation energy was 43.9 kJ/mol as determined using the Arrhenius equation. According to the statistical parameters of the correlation coefficient (R^2), root mean square error (RMSE) and the sum of squared errors (SSE), the modified Page model was selected as best for representing the correlation between moisture ratio and drying time.

Keywords: drying activation energy; drying model; moisture effective diffusivity; pulsed air jet impingement; winter jujube slices

Jujube, a fruit tree which is found worldwide, has been rapidly developed over many years in the Xinjiang province of China because of its unique climate. Winter jujube contains 18 kinds of amino acids and vitamins known as 'live vitamin pills'. Winter jujube is a late-maturing variety of the fruit (Liu *et al.* 2011). The postharvest shelf-life of winter jujubes is short and they can only be stored for up to ten days under uncontrolled conditions (Li *et al.* 2016). Therefore, most farmers dry fresh jujube in order to extend the storage period (Zozio *et al.* 2014). The source of jujube slices are less restrictive compared with whole jujubes. The local damage jujubes and small jujube can also be processed into jujube slices to achieve the maximum economic benefit. Dried jujube slices can be consumed as a snack, as well as in tea, soup, porridge and other foods (Fang 2010; Gao *et al.* 2012; Doymaz *et al.* 2012; Kumar *et al.* 2014; Wojdylo *et al.* 2016).

Natural drying is the traditional method of drying. This method uses the radiant heat of the sun or the wind to evaporate the moisture in the jujube. However, this drying method is limited by natural conditions. The drying time is very long, and the drying temperature is difficult to control. Moreover, pollution caused by sandstorms reduces the product quality and especially leads to the loss of vitamin C.

Pulsed air jet impingement drying is a type of intermittent drying which can effectively prevent the excessive drying of a material by variation of the drying conditions (Berk 2013). There are many ways to realise intermittent drying, such as changing dry-

Supported by the National Natural Science Foundation of China, Grant No. 31360411.

https://doi.org/10.17221/258/2017-CJFS

ing temperature, humidity and wind speed (Kumar *et al*. 2014). Pulsed air jet impingement drying has a higher convective heat transfer coefficient and lower rate of surface damage compared with traditional hot-air drying, because it allows enough time for moisture migration from the interior to the surface of a material during the drying process (Gao 2000). This drying method has been already widely and successfully applied to paper, textiles and agricultural products such as bitter melons (Xue *et al*. 2017), purple sweet potatoes (Li *et al*. 2013), seeds (Yao *et al*. 2011), walnuts (Zhao & Xiao 2015) and Peking duck (Ma *et al*. 2006) among other.

In this paper, the pulsed air jet impingement drying characteristics of winter jujube slices were studied and the effects of drying temperature, wind speed and pulsation rate on drying curves, moisture effective diffusivity and drying activation energy were determined. We hope that our study can provide technical support as well as a valuable theoretical basis for the drying of jujube slices.

MATERIAL AND METHODS

Experimental device. The drying device as shown in Figure 1 was fabricated by the Drying Technology and Equipment Laboratory of Shihezi University and mainly consists of a control system, centrifugal fan, heating system, air distribution room, drying room, nozzle module, material tray and machine frame (Wang *et al*. 2011).

Protocol. Air was continuously blown into the heating system by the centrifugal fan. After heating, hot air was sent into the air distribution room through an intake tube. Then, the heated air was uniformly distributed

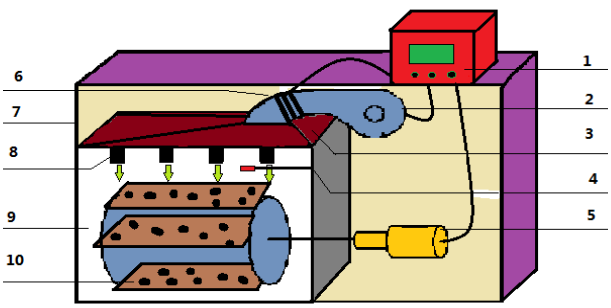

Figure 1. Structure of the pulsed air jet impingement dryer: 1 – control system; 2 – centrifugal fan; 3 – air distribution room; 4 – temperature sensor; 5 – motor; 6 – heating system; 7 – frame; 8 – injector; 9 – drying room; 10 – material tray

into a branch nozzle after which air flow was directed into the drying room to dry the materials through the nozzle module. Finally, the used air was return to the centrifugal fan through the recycle tube. There were six material trays on the material frame, driven by a motor with a constant rotational speed. When the material tray is on top of the drying room, the air impact effect is the strongest. When the material tray is on the bottom, the air impact effect is the weakest.

The adjustable parameter ranges of the drying device were the following: wind speed 4–13 m/s, wind temperature 25–90°C, pulsation rate 3–9 rpm. The other major equipment used were an electronic scale (Yueping Scientific Instruments Co., Ltd., China) and an electric blast-drying oven (Yiheng Science and technology Co., Ltd., China).

Experimental materials. Fresh winter jujubes, of the same degree of maturity and of similar size, were bought from the Shihezi Comprehensive Wholesale Market. The surface of the winter jujubes was cleaned, before transfer to a refrigerator for 24 h at a temperature of 4 ± 1°C and relative humidity of 96 ± 2%. The dry basis moisture content of jujube flesh was determined to be 84 ± 1%. Moisture content was determined by heating in a drying oven at 105°C for 48 hours (AOAC 1990; Rodrigues & Fernandes 2007).

Experimental method. Fresh winter jujubes were cut into 7 ± 1 mm slices uniformly and placed on the material trays (40 × 20 cm, stainless steel mesh) in a single layer. The weight of fresh jujube slices in every material tray was about 100 ± 5g. Before the experiments, drying parameters were established, and then power was switched on and the drying machine was preheated. When the temperature reached the desired value, the material trays with winter jujube slices were placed on the material frame. The material trays were weighed once per hour and the experimental data were recorded. The experiment was stopped when the moisture content of winter jujube slices was less than 12%.

The specific experimental arrangement is shown in Table 1; each group of experiments was performed three times.

Calculation method. The dry basis moisture ratio (*MR*) of winter jujube slices during experiments was calculated using the following formula:

$$MR = M_t - M_0 \quad (1)$$

where: M_0 – initial dry basis moisture content (g/g); M_t – dry basis moisture content at time *t* (g/g)

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Table 1. Single factor experiment design and parameters

Number	Temperature (°C)	Wind speed (m/s)	Rotation rate (rpm)
1	55	8	7
2	60	8	7
3	65	8	7
4	70	8	7
5	75	8	7
6	80	8	7
7	70	6	7
8	70	7	7
9	70	9	7
10	70	10	7
11	70	10	4
12	70	10	5.5

The drying rate (DR) of jujube slices during experiments [g/(g × h)] was calculated using the following formula:

$$DR = (M_{t1} - M_{t2})/(t_2 - t_1) \quad (2)$$

where: t_1 and t_2 – the drying time at different points during the drying process (h); M_{t1} and M_{t2} – the dry basis moisture content of samples at times t_1 and t_2 (g/g)

The moisture effective diffusivity (D_{eff}) of materials (m^2/s) was calculated using the following formula (Afzal & Abe 1998; Doymaz 2007):

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{L^2} t \quad (3)$$

where: L – slice thickness (m); t –drying time (s)

The drying activation energy (Ea) of materials (kJ/mol) was calculated as follows:

$$D_{eff} = D_0 \exp[-E_a/R\ (T + 273.15)] \quad (4)$$

where: D_0 – the constant diffusivity basis (m^2/s); R – universal gas constant with 8.314 [J/(mol·k)]; T – drying temperature (°C)

Data processing and model analysis. Data were analysed using SPSS17.0 software. The parameters of models were estimated using a nonlinear regression procedure based on the Gauss-Newton algorithm. The goodness of fit of the experimental data to all models was evaluated using the coefficient of determination (R^2), the error sum of squares (SSE) and root-mean-square error (RMSE). The bigger the R^2, the smaller the RMSE and SSE and the better the goodness of fit. (Doymaz 2007; Lin & Wang 2010). These parameters were calculated from the following formulas:

$$R^2 = \frac{\sum_{i=1}^{N}(MR_i - MR_{pre,i})(MR_i - MR_{exp,i})}{\sqrt{\left[\sum_{i=1}^{N}(MR_i - MR_{pre,i})^2\right]\left[\sum_{i=1}^{N}(MR_i - MR_{exp,i})^2\right]}} \quad (5)$$

$$SSE = \sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2 \quad (6)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{\frac{1}{2}} \quad (7)$$

where: MR_i – moisture ratio at time i; $MR_{\exp,i}$ – measured moisture ratio; $MR_{\mathrm{pre},i}$ – predictive moisture ratio; N – the number of groups of experimental data

RESULTS AND DISCUSSION

Effects of drying temperature, wind speed and pulsation rate. The drying curves at different temperatures, wind speeds and pulsation rates are shown in Figure 2. Figure 2A shows that when the drying temperatures were 55, 60, 65, 70, 75, and 80°C, the total drying times were 13, 11, 9, 7, 6, and 5 h, respectively, at a wind speed of 8 m/s and pulsation rate of 7 rpm. Thus, drying rate increased with an increase in the drying temperature. When the temperature was 70°C, drying time was reduced by 33.33% compared to 55°C. When the temperature was higher than 70°C, the drying time was shortened markedly. It is possible that at higher temperatures the degree of freedom of the moisture is lower. Therefore, the diffusion speed of moisture through the material and the evaporation of moisture on the material surface are faster. These results are similar to those of Yi (2015) that the temperature of hot air has a significant effect on red jujube drying. Wang *et al.* (2016) reported that increased temperature promotes moisture diffusion during the hot air drying of apple slices. These results regarding drying temperature are also supported by the work of Zhang *et al* (2012), who examined the effect of temperature on carrot slices during a hot air-drying process.

Drying temperature should not exceed 80°C, otherwise the quality of dried products is markedly diminished (Rodrigues & Fernandes 2007).

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Figure 2B shows that at wind speeds of 6, 7, 8, 9, and 10 m/s the total drying times were 9, 9, 8, 8, and 8 h at a drying temperature of 70°C and pulsation rate of 7 rpm. The drying rate showed an increasing trend with increasing wind speed. When the wind speed was 10 m/s, the drying time was decreased by 20% compared to 6 m/s. The reason for this phenomenon is that the intensity of convective heat transfer is increased at higher wind speeds. Therefore, the jujube slices are subject to more heat per unit time, which accelerates the water evaporation rate of the fruit.

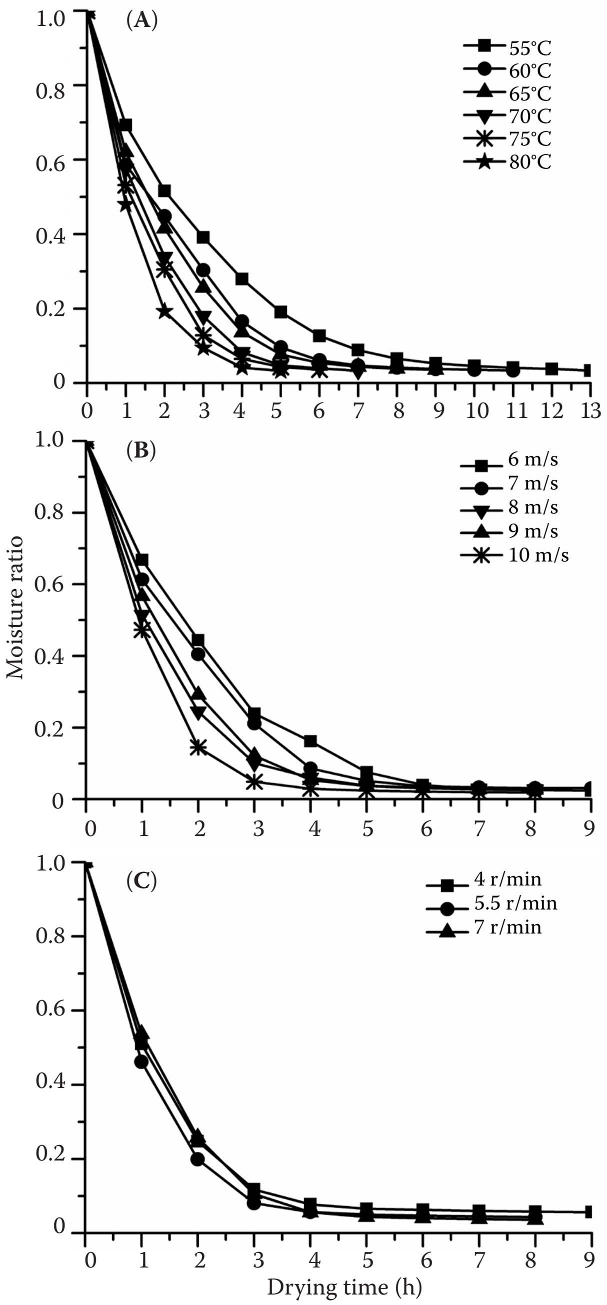

Figure 2. The moisture ratio at different (**A**) drying temperatures, (**B**) wind speeds, (C) pulsation rates and drying times of jujube slices

Figure 2C shows that when pulsation rates were 4, 5.5, and 7 rpm, the total drying times were 9, 8, and 8 h, respectively, at a drying temperature of 70°C and wind speed of 10 m/s. Total drying time was 11.11% shorter at a pulsation rate of 7 rpm compared to 4 rpm. There was an increasing trend in the drying rate with increasing pulsation rate. This is because at higher pulsation rates there is a longer total time of air jet impact. It also leads to the jujube slices receiving more heat per unit time and further promotes the effect of water evaporation.

Table 2 shows the single factor variance analysis of the effects of drying temperature, wind speed and pulsation rate on drying rate. The variance analysis showed that, $P_{\text{drying temperature}} < 0.01$, $P_{\text{wind speed}} = 0.178 > 0.05$, $P_{\text{pulsation rate}} = 0.085 > 0.05$, which reveals that the effect of drying temperature was extremely significant, while those of wind speed and pulsation rate were not significant. In accordance with this result, Yang *et al* (2014) reported that hot air temperature was the main factor that influenced the drying process of rapeseed. The findings of Chen *et al.* (2017), who showed that the hot air-drying process of papaya slices is affected by hot air temperature, are also similar to those of this study. Similarly, Chang *et al.* (2013), in their optimisation of the technological parameters for the hot air-drying of lemon, found that air temperature has a great influence on the drying rate.

Table 2. ANOVA of different drying temperatures, wind speeds, and pulsation rates

Source	Sum of squares	Freedom	Mean square	F	P
Drying temperature	165.22	5	33.04	24.78	< 0.001
Error	14.67	11	1.33		
Total	179.88	16			
$a = 0.05$; $F_{0.05}$ (5, 11) = 3.20					
Wind speed	12.00	4	3.00	1.96	0.178
Error	15.33	10	1.53		
Total	27.33	14			
$a = 0.05$; $F_{0.05}$ (4, 10) = 3.48					
Pulsation rate	1.1214	2	0.607	4.86	0.085
Error	0.500	4	0.125		
Total	1.714	6			
$a = 0.05$; $F_{0.05}$ (2, 4) = 6.94					

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Effective water diffusion coefficient. Figure 3 shows the drying rate curves for drying time at different temperatures, wind speeds and pulsation rates. The results show that the whole drying process of winter jujube slices can be described as a falling-rate process. It is possible that drying rate depends on the rate of internal moisture migration and that the surface moisture evaporation rate exceeded the internal moisture migration rate of winter jujube slices, resulting in the formation of a hard shell on the surface of the material. This hard shell would then impede further evaporation of moisture. An experimental study on chrysanthemum reported by Dai *et al.* (2017) found that the drying of this plant using a heat pump is a falling-rate process. Sheng *et al.* (2016) found that the drying rate gradually decreases as the moisture content of banana chips decreases. This is because the lower the water content of the banana chips, the lower the rate of water migra-

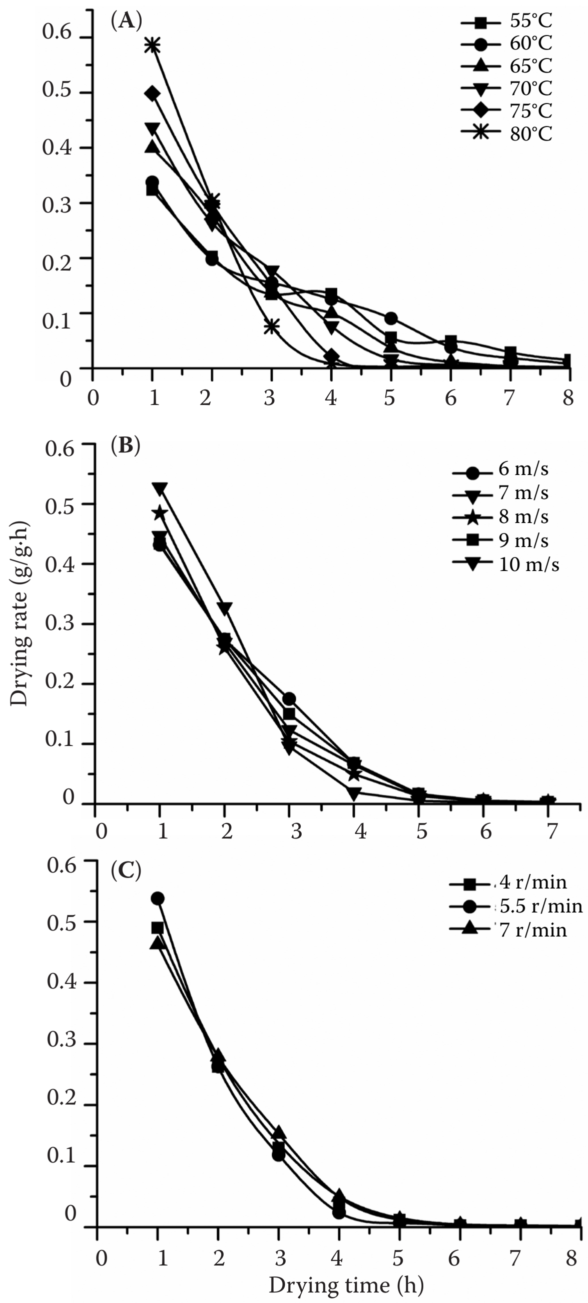

Figure 3. The drying rate at different at different (**A**) drying temperatures, (**B**) wind speeds, (C) pulsation rates and drying times of jujube slices

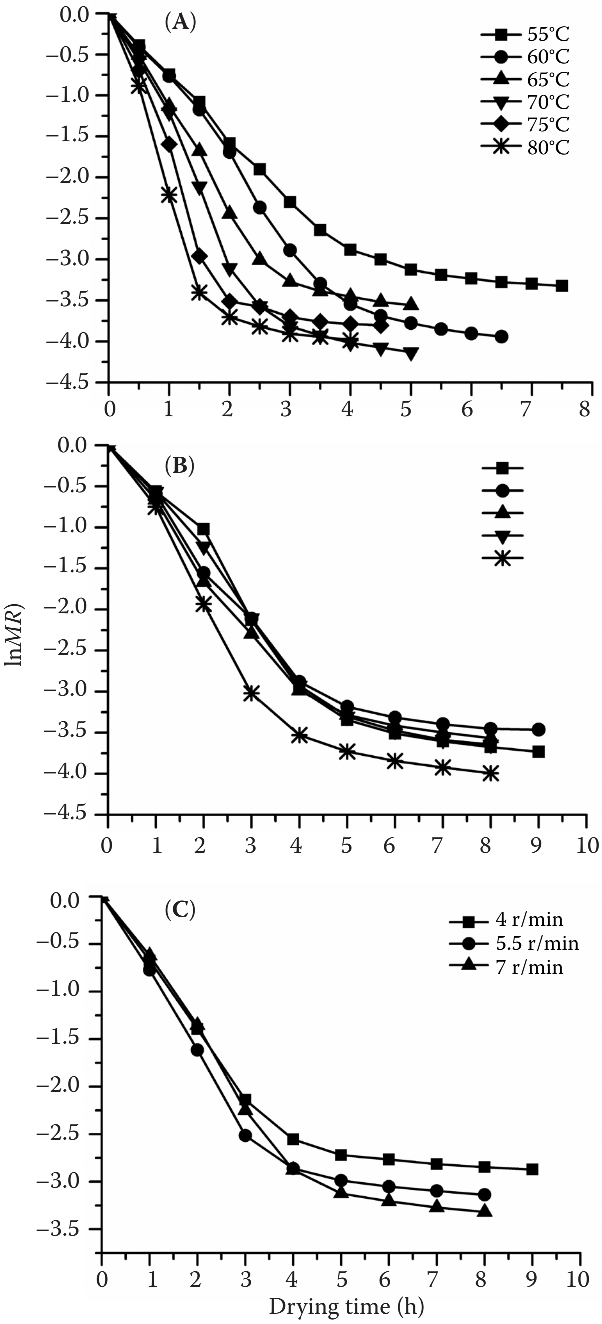

Figure 4. The ln*MR* at different at different (**A**) drying temperatures, (**B**) wind speeds, (C) pulsation rates with drying times of jujube slices

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Table 3. Moisture effective diffusion coefficient at different drying conditions

Number	Linear regression fitting formula	R^2	D_{eff} (10^{-9} m²/s)
1	$\ln MR = -3.079 \times 10^{-4}\ t + 0.0975$	0.9655	1.52
2	$\ln MR = -4.161 \times 10^{-4}\ t + 0.3510$	0.9722	2.07
3	$\ln MR = -5.229 \times 10^{-4}\ t + 0.4243$	0.9735	2.60
4	$\ln MR = -6.165 \times 10^{-4}\ t + 0.4853$	0.9556	3.06
5	$\ln MR = -7.915 \times 10^{-4}\ t + 0.7153$	0.9495	3.93
6	$\ln MR = -9.925 \times 10^{-4}\ t + 0.9368$	0.9203	4.93
7	$\ln MR = -5.613 \times 10^{-4}\ t + 0.3584$	0.9422	2.79
8	$\ln MR = -5.986 \times 10^{-4}\ t + 0.4885$	0.9648	2.98
9	$\ln MR = -6.286 \times 10^{-4}\ t + 0.5679$	0.9722	3.13
10	$\ln MR = -6.818 \times 10^{-4}\ t + 0.3261$	0.9154	3.39
11	$\ln MR = -5.713 \times 10^{-4}\ t + 0.4189$	0.9651	2.84
12	$\ln MR = -6319 \times 10^{-4}\ t + 0.4196$	0.9463	3.14
13	$\ln MR = -7382 \times 10^{-4}\ t + 0.7944$	0.9964	3.68

tion from the interior to the surface of banana chips, resulting in a decrease in the drying rate. Wang *et al.* (2014) studied the hot air-drying characteristics and dynamics of peanut drying and found that the hot air-drying of peanuts includes an initial short drying stage in which drying speed is increasing, generally followed by a drying stage in which speed is falling. This finding is in line with Zhao *et al.* (2016) who showed that there was no constant drying rate period during the drying of lotus seed and that the entire drying process occurred in a falling-rate manner.

The moisture effective diffusion coefficients were calculated using Fick's second law.

Formula (3) showed that ln*MR* is linear with the *t*. Figures 4 shows the curves of ln*MR* with drying time at different temperatures, wind speeds and pulsation rates. The moisture effective diffusion coefficients calculated for the drying process are shown in Table 3.

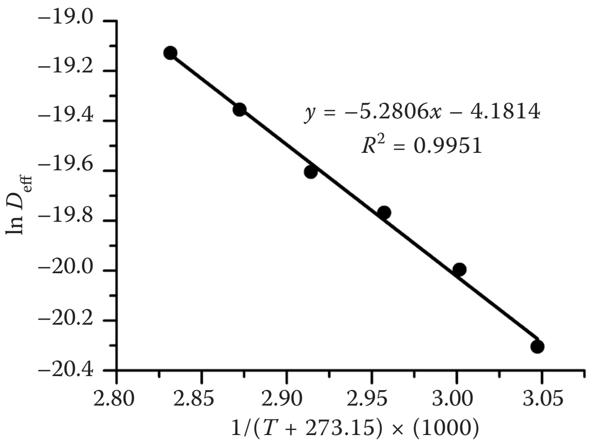

Figure 5. The relationship of lnDeff and drying time

Drying activation energy at different drying temperatures. The drying activation energy is the starting energy needed to remove a mole of moisture during the drying process. The higher the activation energy, the harder it is to dry the material. There is a linear relationship between $\ln D_{eff}$ (the natural logarithm of the water effective diffusion coefficient) and $1/(T + 273.15)$ from formula (4), and the slope is given by E_a/R. The curves showing the relationship between the moisture effective diffusion coefficients and drying temperatures are shown in Figure 5.

The drying activation energy E_a is 43.90 kJ/mol according to the linear regression equation in Figure 5, which means that the minimum energy needed for removal of one mole of moisture during the drying process of winter jujube slices is 43.9 kJ.

Establishment and verification of mathematical models

Determination of the drying model. Several common mathematical models to describe the thin layer

Table 4. Classic thin-layer drying models of fruits and vegetables

Number	Model name	Model equation
1	Lewis	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified	$MR = \exp[-(kt)^n]$
4	Henderson & Pabis	$MR = a\exp(-kt)$
5	Two term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$
6	Wang & Singh	$MR = 1 + at + bt^2$

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drying of fruits and vegetables (Togru 2005; Wang *et al*. 2007) are listed in Table 4. The R^2, *RMSE* and *SSE* parameters for thin-layer winter jujube slices are shown in Table 5.

Drying model fitting. Table 5 shows that the R^2 of the modified Page model and the two-term model are

Table 5. R^2, RMSE, and SSE values of thin-layer drying model parameters

Name	Temperature (°C)	R^2	RMSE	SSE
Lewis MR exp($-kt$)	55	0.9951	0.01961	0.0058
	60	0.9966	0.01762	0.0040
	65	0.9969	0.01758	0.0031
	70	0.9959	0.02025	0.0041
	75	0.994	0.02492	0.0056
	80	0.9955	0.02223	0.0040
Page MR = exp($-ktn$)	55	0.9955	0.01896	0.0050
	60	0.9972	0.01583	0.0030
	65	0.997	0.01729	0.0027
	70	0.998	0.01402	0.0018
	75	0.9965	0.01897	0.0029
	80	0.9974	0.01694	0.0020
Modified MR = exp $[-(kt)n]$	55	0.9958	0.01896	0.0050
	60	0.9975	0.01583	0.0030
	65	0.9973	0.01729	0.0027
	70	0.9982	0.01402	0.0018
	75	0.9969	0.01897	0.0029
	80	0.9977	0.01694	0.0020
Henderson & Pabis MR = $a$exp ($-kt$)	55	0.9949	0.02018	0.0057
	60	0.9964	0.01812	0.0039
	65	0.9966	0.01831	0.0030
	70	0.9957	0.02091	0.0039
	75	0.9934	0.02615	0.0055
	80	0.9949	0.02365	0.0039
Two term MR = $a$exp ($-k_0t$) + $b$exp($-k_1t$)	55	0.9952	0.02174	0.0057
	60	0.997	0.01886	0.0036
	65	0.9984	0.01496	0.0016
	70	0.9965	0.02247	0.0035
	75	0.9943	0.02992	0.0054
	80	0.998	0.01870	0.0017
Wang & Singh MR = 1 + at + $bt2$	55	0.8852	0.09869	0.1364
	60	0.9277	0.08435	0.0854
	65	0.9173	0.09528	0.0817
	70	0.8915	0.11010	0.1091
	75	0.8582	0.12880	0.1326
	80	0.8295	0.14640	0.1534

Table 6. ANOVA of the regression model coefficient n and K

Model	Sum of squares	Free degree	Mean square	F	P
Coefficient *n*					
Regression	0.122	2	0.061	6.509	0.015
Residual error	0.093	10	0.009		
Total	0.215	12			
Coefficient *k*					
Regression	0.243	2	0.121	38.585	< 0.001
Residual error	0.031	10	0.003		
Total	0.274	12			

$a = 0.05$; $F_{0.05}$ (10, 2) = 4.10

larger, while the RMSE and SSE are smaller than in the other models. The modified Page model is more suitable for describing the pulsed air-jet impingement drying characteristics of winter jujube slices because the two-term model has more parameters. The relationships among drying constant k and n, drying temperature, wind speed and pulsation rate are shown in the formulas (9) and (10) applying multiple linear regression analysis in SPSS17.0.

$$k = 1.119 + 0.021\ T + 0.034\ V \quad (8)$$

$$n = 0.363 + 0.118\ R + 0.011\ T \quad (9)$$

where: T – drying temperature (°C); V – wind speed (m/s); R – pulsation rate (rpm)

The variance analysis of the model coefficients k and n is shown in Table 6. Both p_k and p_n are less than 0.05, which means that the regression equation is valid.

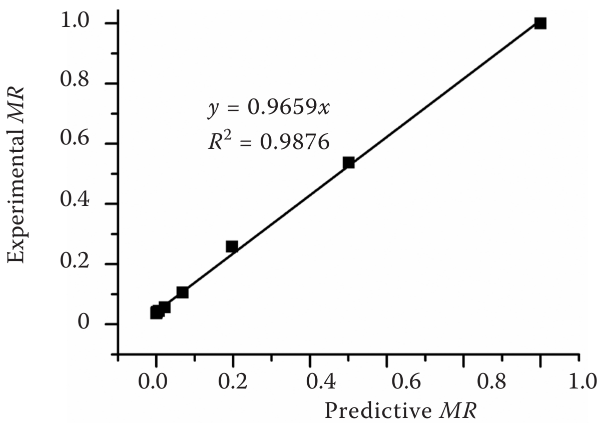

Figure 6. The relationship of experimental MR and predictive MR

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Formula (10) expresses the actual relationship between *MR*, *T*, and *t* by combining formulas (8) and (9) into a Modified Page model equation.

$$MR = \exp [-[(-3 \times 10^{-5} T^3 + 0.0062 T^2 - 0.4017 T + 8.7941) t]^\wedge (7 \times 10 - 5 T^3 - 0.0146 T^2 + 0.9564 T - 19.989)] \quad (10)$$

Model validation. The experimental values and values predicted by the modified Page model at a temperature of 70°C, wind speed of 10 m/s and pulsation rate 7 of rpm, are shown in Figure 6. The relationship between the experimental values and the predicted values is $y = 0.9659x$, $R^2 = 0.9876$. Therefore, the modified Page model equation is suitable for representing the rate of change of pulsed air jet impingement drying characteristics of winter jujube slices over the studied range of experimental parameters.

CONCLUSIONS

In this study, we determined the pulsed air jet impingement drying characteristics of winter jujube slices at different drying temperatures, wind speeds and pulsation rates. The experimental data were processed with SPSS17.0 software. Over the experimental range tested, the results are as follows:

(1) The single factor analysis of variance showed that the effect of drying temperature on the drying rate was extremely significant, while the effects of wind speed and pulsation rate were not significant. The drying rate increased with the increasing drying temperature, but the drying temperature should not exceed 80°C.

(2) The whole drying process was a falling-rate process. The effective diffusion coefficient of moisture in the experimental range increased with the increasing drying temperature, wind speed and pulsation rate. The effective diffusion coefficient of moisture was in the range 1.52–4.93 × 10^{-9} m^2/s. The drying activation energy was 43.90 kJ/mol.

(3) The experimental data were fitted and compared with six types of thin-layer drying models. The modified Page model was found to be the most suitable, in the following parameter ranges: drying temperature 55–80°C, wind speed 6–10 m/s, pulsation rate 4–7 rpm. Thus, the modified Page model can be used to describe the rate of change of the moisture ratio by comparing the values predicted by the model with the experimental values.

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Received: 2017–07–04
Accepted after corrections: 2018–06–11