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Colour Change and Kinetics of Winter Jujube Slices during Pulsed Air-Jet Impingement Drying

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Abstract

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The colour and the characteristics of colour change curves of winter jujube slices at different temperatures (55, 60, 65, 70, and 75°C) by the single factor experiment during pulsed air-jet impingement drying were stidied. The experimental data of colour difference (ΔE^*) were fitted and verified by classic colour change model of thin fruit and vegetable. The results showed that L^*(whiteness/darkness) and $-a^*$ (redness/greenness) of winter jujube slices decreased with the increase of drying time at different drying temperatures, while the change in the early stage was rapid, the latter stage was slow. The b^* (yellowness/blueness) increased with the increase of drying time at different drying temperatures. Under different drying temperatures, the colour difference (ΔE^*) of winter jujube slices increased with the increase of drying time during the drying process, the change in the early stage was rapid, the latter stage was slow. When the drying temperatures were 55, 60, 65 and 75°C, the first order fractional model of the colour difference (ΔE^*) obtained the best fitting results with experimental data. Meanwhile, when the drying temperature was 70°C, the first of the first order mode of the total colour difference (ΔE^*) was the best.

Keywords: CIELab; colour change; pulsed air-impingement drying; winter jujube slices

The colour of jujube is an important symbol for evaluating the freshness and maturity of jujube, and also one of the important indexes for evaluating the quality of jujube slices. In order to improve the drying quality of the material, many scholars at home and abroad have done a lot of research on fruit and vegetable drying (Han & Li 2006; Cheng *et al.* 2011; Yuan *et al.* 2012). During the drying process, the reason why the dried product turns yellow, brown, or black is enzymatic browning and non-enzymatic browning. After the plant tissue is damaged, enzyme browning refers to oxidative discoloration under the action of oxidize and peroxides. Non-enzymatic browning is the production of melanin by amino acids in the material and reducing sugars, and the higher the temperature, the faster the non-enzymatic browning rate. Colour is an important indicator for customers to evaluate commodity value. Therefore, we can detect and monitor the quality changes of jujube slices during drying process.

Xiao *et al.* (2015) studied the colour change characteristics of American ginseng slices using pulsed air-jet impingement drying and fitted the kinetics model of colour. Argyropoulos and Muller (2014) studied the colour change kinetics of lemon balm with hot-air drying, and fitted the colour change model. Olivera *et al.* (2013) studied the colour change and texture of beef during storage, and fitted the colour change model. Ju and Xiao (2013) studied the colour change and drying characteristics of apple slices with

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intermediate wave drying. Ergüneş and Tarhan (2006) studied the colour retention of red pepper by chemical pretreatments during greenhouse and open solar drying. Zhang and Xiao (2012) studied the effects of pretreatment on air impingement drying characteristics and product colour for line pepper. Casati *et al*. (2015) studied the colour degradation kinetics during heat treatment and storage of elderberry juice. Naidn *et al*. 2016 studied the storage temperature on the colour and anthocyanin of blueberry juice. Zhang & Zhang (2014) studied on the colour change of green prickly ash at different drying conditions. Zhang *et al*. (2012) studied on drying characteristics and colour changes of infrared drying eggplant. Wang *et al*. (2014) studied on parameters screening of Yak'Qula and evaluation of colour quality with hot-air drying.

It can be found that the colour change of winter jujube slices is closely related with drying temperature through the pre-experiment and related literature, but there is little related to other factors. Therefore, this paper will study the change the colour low of winter jujube slices at different drying temperatures and use the colour difference (ΔE^*) to describe the colour change law of winter jujube slice under pulsed air-jet impingement drying.

MATERIAL AND METHODS

Experimental device. The pulsed air-jet impingement for drying machine is as showed in Figure 1 (Wang 2011). Other main equipment: electronic scale (JY/YP30002; Shanghai Yueping Scientific Instrument Co., Ltd., China), electrothermal blowing dry box (DHG-9070A; Shanghai Hengyi Technology Co., Ltd., China), colorimeter (SMY-2000SF; Beijing Sheng mingyang Technology Co., Ltd., China).

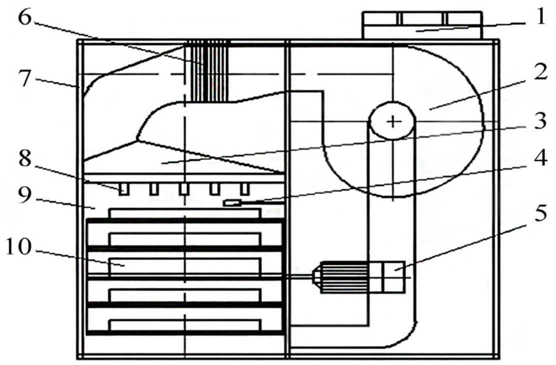

Figure 1. Structure of pulsed air-jet impingement dryer: 1 – control system, 2 – centrifugal fan, 3 – air distribution room, 4 – temperature sensor, 5 – motor, 6 – heating system, 7 – frame, 8 – injector, 9 – drying room, 10 – material tray

Experimental materials. Fresh winter jujubes, bought from Shihezi comprehensive wholesale market, which were same mature degree, shape rules. The longitudinal diameters selected was 2.9 ± 0.5 cm, diameter 2.7 ± 0.5 cm, the moisture content of drying base of winter jujube 84 ± 1%; dried over 24 h continue in the temperature of 105°C. The surface of winter jujubes were cleaned and put them into the freezer which temperature was (4 ± 1°C) and relative humidity was (96 ± 2%), then refrigerated them into the freezer over 24 hours.

Experimental methods. Fresh winter jujubes were cut into 7 ± 1 mm uniform slices, and then put on the material tray that is 40 × 20 cm (stainless steel mesh) in the form of single layer. The weight of fresh winter jujube slices in material tray was about 100 ± 5 g. Before drying, turn on the power and set the drying parameters for preheating the drying machine. Put the material trays on the material frame until the temperature reached the setting temperature. Weighed the material tray once per hour and recorded the experiment data. The experiment was finished until the moisture content of drying base of winter jujube slices was less than 12%.

The main controllable factors were air temperature (55, 60, 65, 70, 75, and 80°C), wind speed (6, 7, 8, 9, and 10 m/s), pulsation rates (4, 5.5, and 7 rpm). The specific experiment arrangement is in Table 1, each group of experimental repeated 3 times.

Establishment of colour change model

The colour changes kinetics curves. The CIELAB colour system was used to describe quantitatively the colour change kinetics during the drying process. The $L^*a^*b^*$ of winter jujubes slices were measured at different drying temperatures by isochronal sampling. The ΔE^* of winter jujube slices' surface which dynamic change with the drying time at different drying temperatures was calculated by the formulas (1–4). Then drew the kinetics curves of $L^* - t$, $a^* - t$, $b^* - t$, and $\Delta E^* - t$ (Xiao 2010).

$$\Delta L^* = L^* - L_0^* \tag{1}$$

$$\Delta a^* = a^* - a_0^* \tag{2}$$

$$\Delta b^* = b^* - b_0^* \tag{3}$$

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$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (4)$$

where: L^* = 0 – black, L^* = 100 – white; the range of a^* is –60 (pure green) ~ +60 (pure red), greater $+a^*$ – redder; smaller $-a^*$ – greener; the range of b^* is –60 (pure blue) ~ +60 (pure yellow), greater $+b^*$ – yellower, smaller $-b^*$ – bluer; ΔE^* – colour change of materials (Aysum *et al.* 2002; Nuria *et al.* 2008)

The colour change kinetic model. The kinetics model of the colour change during drying process generally used the 0-order model, the first-order model and the first-order fractional model, showed in formulas (5–7) (Avila *et al.* 1999; Chen & Ramaswamy 2002; Kumar *et al.* 2006; Kong *et al.* 2007).

$$c = c_0 \pm kt \quad (5)$$

$$c = c_0 \exp(\pm kt) \quad (6)$$

$$(c - c_f)/(c_0 - c_f) = \exp(\pm kt) \quad (7)$$

where: C_0 – initial value of colour; C – colour value at the time t; C_f – final value of colour; t – time; k – constant, parameter change rate; $^-$ parameter value is reduced, $^+$ parameter value is rising

The experiment data was disposed by Excel software, and the three models were fitted, the coefficients were calculated. The results of the degree of fitting were evaluated according to the determination coefficient R^2. The higher R^2 of fitting model was selected to describe colour change law of winter jujube slices. The equations of model parameters in different drying temperature were established by regression analysis, and the kinetics model was established to provide theoretical and technical support for predicting, analysing and controlling the colour change of winter jujube slices during drying process.

RESULTS AND DISCUSSION

Kinetics curve. The L^*, a^*, b^* and ΔE^* of pulsed air-jet impingement drying of winter jujube slices are showed in Figure 2. The L^* and a^* of the winter jujube slices decreased with the increase of drying time at different temperatures, while the b^* and ΔE^* increased with the increasing drying time. The results showed that the L^* decrease during drying process, the surface colour is more and more yellow, the colour difference between dried winter jujube slices and fresh winter jujube slices are getting bigger and bigger. The reason may be the browning reaction of the winter jujube slices during the drying process (Sacilik & Elicin 2006; Liu & Wang 2011). The reflectivity of the surface of the winter jujube slices was decreased, the green components of the winter jujube slices were degraded and the red compo-

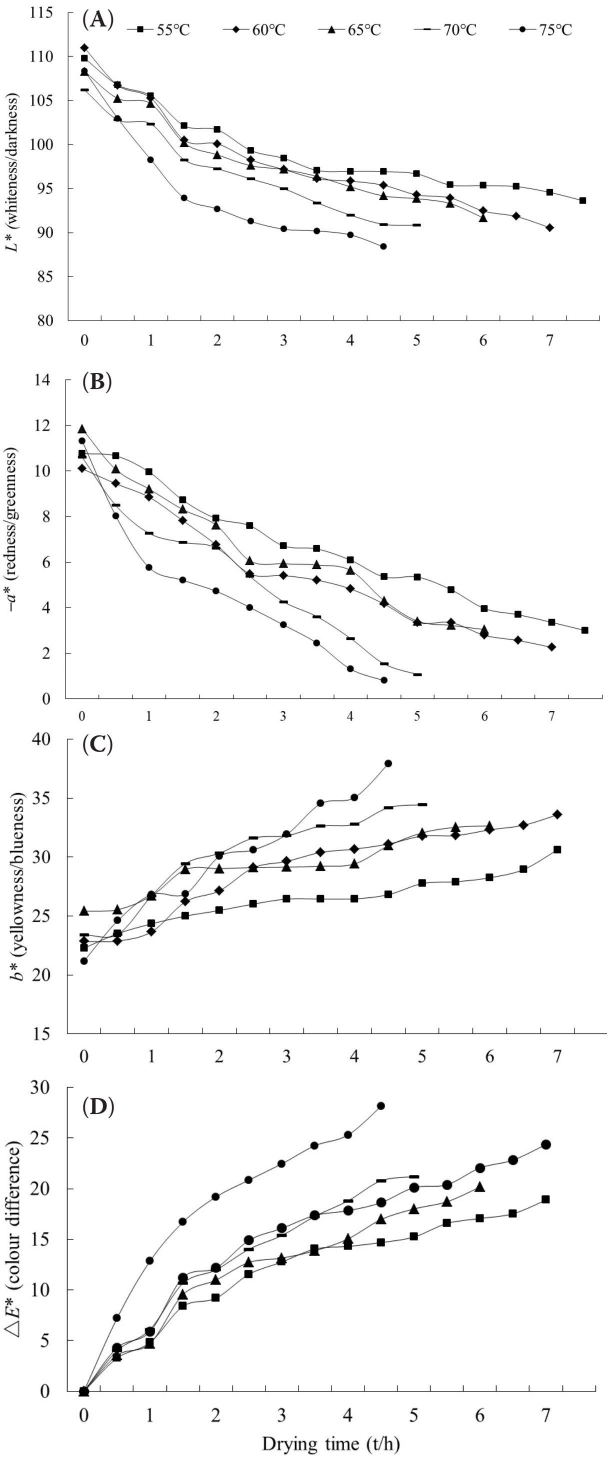

Figure 2. The change curve of (**A**) L^*, (**B**) a^*, (**C**) b^*, (**D**) ΔE^* with drying time at different drying temperatures

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nents were formed, so the a^* and L^* are decreased, the b^* and ΔE^* are increased.

The L^*, a^*, and ΔE^* changed rapidly in the early stage of drying process at different drying temperatures, but slowly in the later stage. The higher temperature lead the more rapidly change. The b^* was linear relationship with the drying time. The reason may be the moisture of winter jujube slices was removed rapidly in the early stage of drying process, browning and mildew reaction were more quickly, brightness of the winter jujube slices surface dropped rapidly (Sacilik *et al.* 2006; Liu & Wang 2011). The higher drying temperature, the mildew reaction more rapidly, the weaker reflection intensity of the light on the surface of the winter jujube slices, the formation of red component was faster, the colour change was more serious with the fresh jujube.

When the drying temperatures were 55, 60, 65, 70, and 75°C, the L^* of winter jujube slices were 93.62, 92.45, 91.67, 90.84, and 88.37, the $-a^*$ were 3, 2.26, 3.04, 1.07, and 0.81, the b^* were 30.63, 33.59, 32.65, 34.44, and 37.93, the colour difference ΔE^* were 18.88, 24.36, 20.17, 21.18, and 28.12. The results showed that: The L^* and $-a^*$ are decreased with the increase of drying temperature, the b^* and ΔE^* are increased with the increase of drying temperature. The lower drying temperatures are beneficial to reduce the colour change of L^*, $-a^*$, b^*, and ΔE^* during the drying process.

Kinetic change model of colour difference ΔE*. The experimental data was fitted with the 0th order, first order and first order fraction model to calculate a fit model parameters and the squared sum determination coefficient R^2 that is showed in Table 2.

When the drying temperature was 55°C, the R^2 of the three models were 0.8043, 0.7782 and 0.9816, respectively. The first order fraction model was the best. When the drying temperature was 60°C, the R^2 which the three models fitted with the experimental

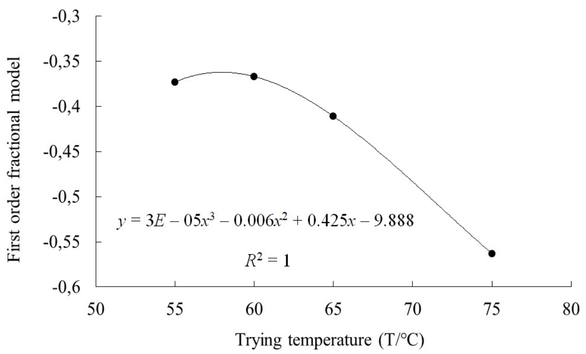

Figure 3. Regression relationship between the parameters of first order model and the drying temperatures

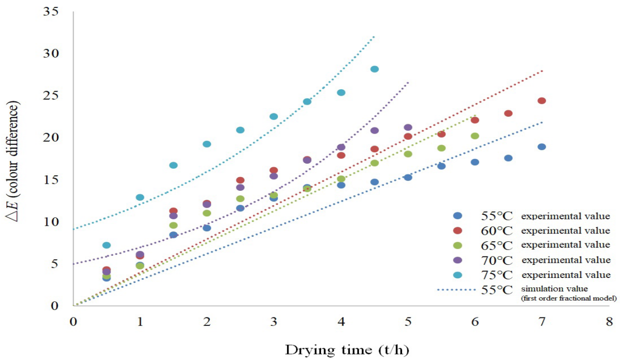

Figure 4. Chromatic aberration value ΔE* and simulation values change with drying time at different drying temperatures

data were 0.9266, 0.8055, and 0.9652, respectively. The first order fraction model was the best fitted with the experimental data. When the drying temperature was 65°C, the R^2 were 0.8785, 0.7779, and 0.9489, respectively. The first order fraction model was the best fitted with the experimental data. When the drying temperature was 75°C, the R^2 were 0.7936, 0.8179, and 0.996, respectively, the first order fraction model was the best fitted with the experimental data. So when the temperatures were 55, 60, 65 and 75°C the colour change kinetics model of the pulsed air-jet impingement drying of winter jujube slices as follows:

$$\frac{\Delta E^*_{55}-18.88}{3.27-18.88}=\exp(0.373t) \tag{8}$$

$$\frac{\Delta E^*_{60}-24.36}{4.28-24.36}=\exp(0.367t) \tag{9}$$

$$\frac{\Delta E^*_{65}-20.17}{3.55-20.17}=\exp(0.411t) \tag{10}$$

$$\frac{\Delta E^*_{75}-28.12}{7.20-28.12}=\exp(-0.563t) \tag{11}$$

where: ΔE^*_{55}, ΔE^*_{60}, ΔE^*_{65}, ΔE^*_{75} – colour difference value of winter jujube slices when drying temperature are 55, 60, 65, and 75°C; t – drying time (h)

When the drying temperature was 70°C, the determination coefficients R^2 were 0.8084, 0.8541 and 0.8006, respectively, and the first order model was the best fitted with the experimental data. When the temperature was 70°C, the kinetic model of the pulsed air-impingement drying of winter jujube slices, as follows:

$$\Delta E^*_{70} = 4\exp(-5.93t) \tag{12}$$

where: ΔE^*_{70} – colour difference ΔE^* when the temperature is 70°C; t – drying time (h)

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Table 1. Single factor experiment design and parameters

N	T (°C)	W (m/s)	R (rpm)
1	55	8	6
2	60	8	6
3	65	8	6
4	70	8	6
5	75	8	6
6	80	8	6
7	70	6	6
8	70	7	6
9	70	9	6
10	70	10	6
11	70	10	4
12	70	10	5.5
13	70	10	7

N – serial number; T – temperature; W – wind speed; R – speed

The relationship between the model parameters and the drying temperature were analysed by regression analysis which showed in Figure 3. The regression relationship between the parameter k of the first order fraction model and the drying temperature (T) as follows:

$$k = 3 \times 10^{-5}T^3 - 0.0062T^2 + 0.4251T - 9.888 \quad (13)$$

where: T – 55, 60, 65 and 75°C

Therefore, the model expressed colour difference ΔE^* of the pulsed air-jet impingement dryer of winter jujube slices as follows:

$$\frac{\Delta E^*_{55\sim75} - \Delta E^*_f}{\Delta E^*_0 - \Delta E^*_f} = exp[(3\times10^{-5}T^3 - 0.0062T^2 + 0.425\mathrm{T} - 9.888)t] \quad (14)$$

$$\Delta E^*_{70} = 4\ \exp\ (-5.93t) \quad (15)$$

where: ΔE^* – colour difference of winter jujube slices during drying process; ΔE^*_0 – model constant. When the drying temperatures are 55, 60, 65, and 75°C, the values are –0.373, –0.367, –0.411, and –0.563; T – drying temperature (°C); range is 55, 60, 65 and 75°C; t – drying time (h)

Figure 4 showed the curve of ΔE^* with drying time t at different drying temperatures, and the variation of colour difference was fitted by the formula (14 and 15) with the drying time. From the fig we can find that when the drying temperatures were 65, 70, and 75°C, it was obvious error between the model simulation value and the experimental data value, especially in the middle and late drying process. When the drying temperature were 55 and 65°C, the error between the model simulation value and the experimental data value was small, which shows that the colour change dynamic variation of the winter jujube slices can be accurately simulated and predicted by the formula (14).

CONCLUSIONS

The colour change law of the pulsed air-jet impingement drying of winter jujube slices was described by the L^*, a^*, b^*, and ΔE^*. The kinetics model of colour change was established by fitting with the 0^{th} order model, the first order model and the first order fraction model. In the range of drying temperature, the main conclusions are as follows:

The L^* of the winter jujube slices at different drying temperatures was decreased with the increasing drying time. The L^* changed rapidly at the early stage of different drying temperatures but the late stage change was slow. The L^* was decreased with the increase of drying temperature, so the lower drying temperature is beneficial to reduce the L^* change during the drying process, a^* of the winter jujube slices at different drying temperatures was decreased with the increase of drying time. The a^* changed rapidly in early stage but it changed slowly at later stage. The a^* was decrease with the increase of the drying temperature. Therefore, the lower drying temperature is beneficial to reduce the change of a^* during the drying process.

The b^* of the winter jujube slices at different drying temperatures was increased with the increasing drying time. The b^* of the pulsed air-jet impingement drying of winter jujube slices was linear with the drying time during the drying process at different drying temperatures. The b^* was increased with the increase of drying temperature.

The ΔE^* of the winter jujube slices at different drying temperatures was increased with the increase of the drying time. The ΔE^* was changed rapidly at early stage of different drying temperatures, but it was changed slowly at the later stage. The ΔE^* was increased with the increase of the drying temperature. Therefore, the lower drying temperature is beneficial to reduce the colour change of winter jujube slices during the drying process.

When the drying temperature was 55, 60, 65, and 75°C, the first order fraction model was the best

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Table 2. The 0th order, first order and first order fractional model fit colour change ΔE^* at different temperatures

Temperature (°C)	Model	C_0	C_f	k	R^2
55	$C = C_0 \pm kt$	3.27		3.1239	0.8043
	$C = C_0 \exp(\pm kt)$	3.27		0.2168	0.7782
	$(C - C_f)/(C_0 - C_f) = \exp(\pm kt)$	3.27	18.88	–0.373	0.9816
60	$C = C_0 \pm kt$	4.28		4.8242	0.9266
	$C = C_0 \exp(kt)$	4.28		0.2706	0.8055
	$(C - C_f)/(C_0 - C_f) = \exp(\pm kt)$	4.28	24.36	–0.367	0.9652
65	$C = C_0 \pm kt$	3.55		3.7719	0.8785
	$C = C_0 \exp(kt)$	3.55		0.216	0.7779
	$(C - C_f)/(C_0 - C_f) = \exp(\pm kt)$	3.55	20.17	–0.411	0.9489
70	$C = C_0 + kt$	4.00		3.9976	0.8084
	$C = C_0 \exp(kt)$	4.00		0.3346	0.8541
	$(C - C_f)/(C_0 - C_f) = \exp(\pm kt)$	4.00	21.18	–0.593	0.8006
75	$C = C_0 + kt$	7.20		7.1849	0.7936
	$C = C_0 \exp(kt)$	7.20		0.2795	0.8179
	$(C - C_f)/(C_0 - C_f) = \exp(\pm kt)$	7.20	28.12	–0.563	0.9960

fitted with the experimental data. When the drying temperature was 70°C, the first order model was best fitted with the experimental data.

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