Drying characteristics and mathematical model of ultrasound assisted hot-air drying of carrots

Luo Denglin*, Liu Juan, Liu Yuhong, Ren Guangyue

(*College of Food and Bioengineering, Henan University of Science and Technology, Luoyang 471023, China*)

Abstract: In order to improve the heat and mass transfer process in hot-air drying, power ultrasound was coupled directly to hot-air drying of fresh carrot slices. The effects of ultrasonic power, radiation distance, hot air velocity and temperature on drying characteristics were studied. In addition, the Page equation was used to fit the ultrasound assisted hot-air drying process of the carrot slices. The results showed that the drying rate of carrot slices increased with the increase of ultrasound power and the decrease of radiation distance. Power ultrasound had a greater enhancement on hot-air drying at lower air velocity (0.5 m/s) and temperature (40ºC), especially at the middle and later periods (controlled by internal diffusion). The drying time of carrot slices using ultrasound assisted hot-air drying was shortened by 37.5% compared to that using hot-air drying at the condition with power of 150 W, radiation distance of 15 cm, air velocity of 1.0 m/s and temperature of 40ºC. All test indicators of the model meet the accuracy requirements, which show that the model can better fit the experimental values.

Keywords: power ultrasound, hot-air drying, carrot slices, drying rate, model

DOI: 10.3965/j.ijabe.20150804.1962

Citation: Luo D L, Liu J, Liu Y H, Ren G Y. Drying characteristics and mathematical model of ultrasound assisted hot-air drying of carrots. Int J Agric & Biol Eng, 2015; 8(4): 124－132.

1 Introduction

In recent years, various combined drying techniques display a number of advantages in the field of drying agricultural products, such as hot air - microwave drying, hot air-IR drying, vacuum-IR drying and hot air-vacuum drying. These combined drying techniques can shorten drying time and improve drying efficiency and the quality of products[1-4].

Received date: 2014-11-01 **Accepted date:** 2015-01-16

Biographies: Liu Juan, Master candidate, Research interests: deep processing of agricultural products. Email: 1213044650@qq.com. **Liu Yunhong**, PhD, Associate Professor, Research interests: drying technology and deep processing of agricultural products. Email: lyunhong@126.com. **Ren Guangyue**, PhD, Professor, Research interests: drying technology and deep processing of agricultural products. Email: guangyueyao@163.com.

***Corresponding author: Luo Denglin,** PhD, Professor, Research interests: drying technology and processing of agricultural products. Mailing address: No. 263, Kaiyuan Avenue, Luolong District, Luoyang city, Henan Province, China. Tel: +86-379-64282342, Email: luodenglin@163.com.

As a new drying technology, power ultrasound has a strong directional spread, a large medium particle vibration acceleration and the capacity of strengthening the heat and mass transfer in hot-air drying process effectively[5-8]. Sun et al.[9] carried out a study to enhance the osmotic dehydration of apples and pears with the application of ultrasound. They found that ultrasonic cavitation had a positive effect on strengthening the osmotic dehydration of fruits. The dehydration rate of materials and dry matter both all increased. Dong et al.[10] studied the influence of ultrasound on the mass transfer rule in the osmotic dehydration process of carrots and further confirmed that ultrasound could effectively strengthen the mass transfer during the osmotic dehydration process of carrots. Fernandes et al.[11] irradiated fresh pineapples for 20 min using ultrasound at a frequency of 25 kHz and an intensity of 4 780 W/m^{2,} before hot-air drying, which increased moisture diffusion coefficient by 45.1% and reduced drying time by 31% in the drying process.

The above methods are used to change the organizational structure of materials through ultrasonic pretreatment in the early drying stage to improve the drying efficiency of hot-air in the post stage. However, these methods usually have some adverse effects on the quality of materials after drying[12]. In fact, apart from changing the organizational structure of materials, the increase of heat and mass transfer efficiency in the process of hot-air drying is an even more important factor. Power ultrasound assisted hot-air drying could take the advantage of the unique effect ultrasound generated above to strengthen the hot-air drying process and to achieve the goal of improving drying efficiency and products quality[13,14]. Therefore, based on the principle that disc-type ultrasonic transducer is easier to achieve acoustic impedance matching with air media, we used a self-designed equipment of ultrasonic assisted hot-air drying for fresh carrot slices and built relevant mathematical models to guide for practical applications.

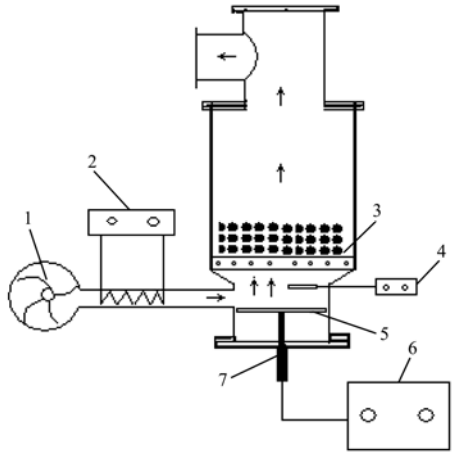
2 Materials and methods

2.1 Materials

Carrots were purchased in Luoyang Zhang supermarket. They were all fresh, not sprouted and pest and disease free. All of carrots were packed with plastic wrap and preserved at 4ºC, which were cut into different thickness slices according to the experiment requirements before drying.

2.2 Experimental equipment

The ultrasound-assisted hot-air dryer was self-designed and a schematic of the dryer is presented in Figure 1. The equipment consists of an air regulator, an electric heater, an air blower, a drying chamber, an ultrasonic generator, an ultrasonic transducer and a vibration disk. The ultrasonic transducer disk is located directly below the net tray to be sure that the material net tray is fully covered. Furthermore, a small air blower for heat dissipation is set up under the transducer to keep the steady operation of ultrasonic transducer. The ultrasound system uses a high-speed embedded microcontroller as the scene CPU and MOS transistor forms switch mode power amplifier circuit. The amplified signal drives the corresponding transducer to work on the best frequency through matching network. The device has the characteristics of automatic frequency search, user-friendly operation interface and convenience to use. It also supports a variety of different operating frequencies with an error running the test prompt flashes to remind, and sound and light alarm.



1. Air blower 2. Electric heater 3. Material net tray 4. Temperature/velocity detector 5. Vibration disk 6. Ultrasonic transducer 7. Ultrasonic generator

Figure 1 Schematic diagram of ultrasound assisted air-hot dying device

2.3 Methods

Carrot slices and drying net tray were weighted respectively before drying, and then put a uniform layer of fresh carrot slices on the drying net tray. The distance of ultrasonic vibration disk from net tray carrying carrot slices was selected 15-25 cm. The ultrasonic frequency, drying temperature and air velocity were set as 21 kHz, 30-70ºC and 0.5-1.5 m/s, respectively. Ultrasonic had a pause for 5 min after working for 5 min. The net tray was weighed every 10 min and then was put back into the dryer immediately for continuous drying. The drying could be stopped when the moisture (dry base) of carrots reduced to lower than 35%. All the tests were conducted in triplicate, and the average values were reported.

2.4 Data processing

Statistical analyses were performed using Origin 8.0 and DPS V3.01.

2.5 Calculation

2.5.1 Dry basis moisture content

Dry basis moisture content was determined refering to GB/T 3543.6-1995, the calculation formula is as follows:

$$D_t = \frac{M_t - M_d}{M_d} \times 100\% \tag{1}$$

where, D_t is dry basis moisture content of the material at time t, %; M_t is the quality of the material at time t, kg; M_d is the dry basis quality of the material, kg.

2.5.2 Drying rate

Drying rate refers to the reduced dry basis moisture content per unit time during the drying process, the calculation formula is as follows:

$$D_R = \frac{D_{t_1} - D_{t_2}}{t_2 - t_1} \tag{2}$$

where, D_R is drying rate, %/min; D_{t_1} is dry basis moisture content at time t_1, %; D_{t_2} is dry basis moisture content at time t_2, %.

2.5.3 Moisture ratio

Moisture ratio could be obtained as follows:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{3}$$

where, M_t is moisture content of material at time t, kg/kg; M_0 is initial moisture content of material, kg/kg; M_e is equilibrium moisture content of material, kg/kg.

2.6 Modeling and precision validation

The drying model equation was determined through the logarithmic linearization of moisture ratio curve. Data analysis was performed using DPS V3.01. Indexes of coefficient of determination (R^2), mean bias error (MBE) and root mean square error (RMSE) were used for the precision validation of the model.

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i}) \tag{4}$$

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

where, N is the number of tested points; MR_{exp} is measured moisture ratio; MR_{pre} is predicted moisture ratio.

3 Results and discussion

3.1 Influence of ultrasonic power on the drying characteristics

Effects of ultrasonic power on the drying curve and drying rate curve of carrot slices were studied when drying temperature, air velocity, ultrasonic radiation distance and carrot slice were 40ºC, 1.0 m/s, 20 cm and 0.3 cm, respectively. The results are shown in Figures 2 and 3.

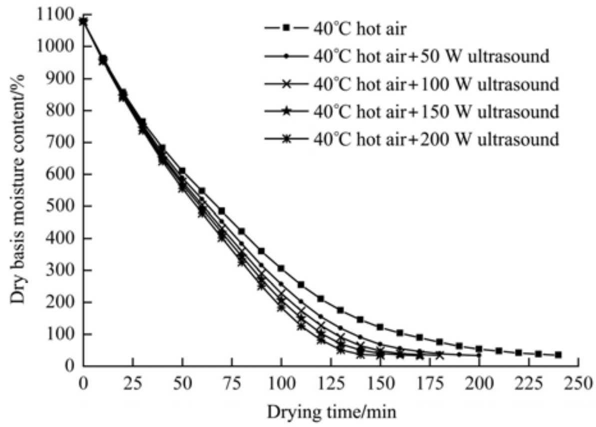


Figure 2 Effect of ultrasonic power on hot-air drying carrot slices

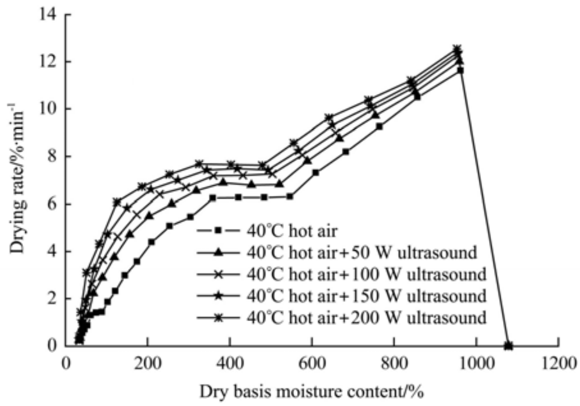


Figure 3 Drying rates of carrot slices under different ultrasonic powers

It was observed that the ultrasound assisted hot-air drying significantly shortened the drying time of carrot slices, and the drying time was shortened with the increase of ultrasonic power (Figure 2). It was obvious that the drying time had a decrease from 240 min to 200 min at ultrasonic power of 50 W. When ultrasonic power was up to 200 W, it only needed 150 min, which decreased by 37.50% compared to that without ultrasonic. The effect of ultrasonic power on the drying rate of carrot slices was shown in Figure 3. In the whole stage of drying, including earlier stage (controlled by external diffusion), middle stage (diffusion equilibrium) and post stage (controlled by internal diffusion), ultrasonic could enhance the drying process obviously, especially for the stage controlled by internal diffusion. For example, when the dry basis moisture content of carrots was in the range of 550%-1079% (the stage controlled by external diffusion), the average drying rate of a single hot-air was about 8.82 %/min. However, when 50 W ultrasonic was applied, the average drying rate was about 9.62 %/min and the increasing rate was 9.07%. When the dry basis moisture content of carrots was in the range of 380%-480% (the stage of diffusion equilibrium), the average drying rate of a single hot-air was about 6.26 %/min. When 50 W ultrasonic was applied, the average drying rate was about 6.85 %/min, which increased by 9.42% compared to that without ultrasonic. When the dry basis moisture content of carrots was in the range of 40%-125%, the average drying rate of a single hot-air was about 1.13 %/min. However, with the application of 50 W ultrasound, the average drying rate was as fast as 1.55 %/min, and the increasing ratio was 37.17%. Generally, it was considered that invigorating effect of ultrasound is due to cavitation effect, mechanical effect and thermal effect. Acoustic cavitation is only occurred in liquid medium. Mechanical vibration can strengthen mass transfer of the vapor-liquid interface effectively. The ultrasound with a frequency of 21 kHz can make hot air particle vibrates back and forth 21 000 times per second. It also can enhance the process of heat and mass transfer in the "dead space" where hot air could not transfer. With the increase of ultrasonic power, the effects of "perturbation", "scouring", "jet" produced by ultrasonic can affect the surface and internal cellular structure of materials and enlarge the aperture between the cell walls, which are contributed to the diffusion transport of intracellular water[15].

3.2 Influence of ultrasonic radiation distance on the drying characteristics

Because ultrasound can not work stably for a long time at a high power (200 W), ultrasonic power was set to 150 W when studied the effects of ultrasonic radiation distance on the drying curve and drying rate curve of carrot slices. Drying temperature, air velocity and thickness of carrot slices were 150 W, 40°C, 1.0 m/s and 0.3 cm, respectively. The results were shown in Figure 4 and Figure 5, respectively.

It could be observed that ultrasonic radiation distance had a significant influence on the drying efficiency of carrot slices in Figure 4. The drying time was obviously

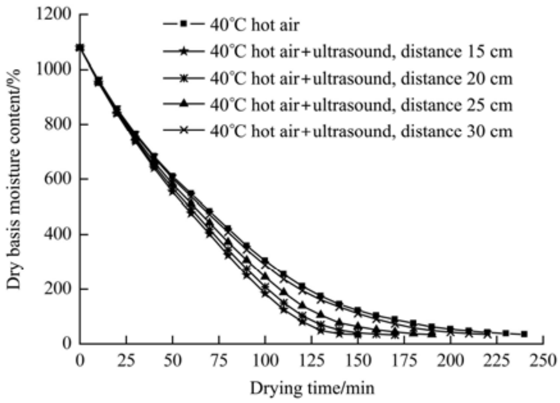


Figure 4 Effect of ultrasonic radiation distance on hot-air drying carrot slices

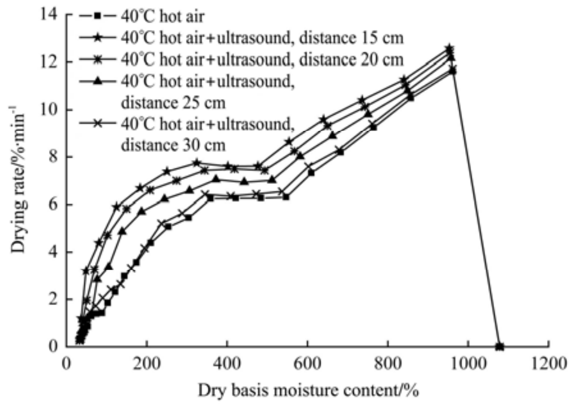


Figure 5 Drying rates of carrot slices under different ultrasonic radiation distances

much shorter and the drying rate was faster at a smaller distance. When the distance was 15 cm, the drying time dropped from 240 min to 150 min compared to that without ultrasonic. The drying times extended to 190 min and 220 min when ultrasonic radiation distance was 25 cm and 30 cm, respectively, indicating that the improvement effect of ultrasound significantly reduced. As shown in Figure 5, the strengthening effect was more obvious with a shorter irradiation distance, especially in the later drying stage (controlled by internal diffusion). For example, the average drying rate (10.41 %/min) increased 18.03% than that without ultrasound when the dry basis moisture content of carrots was in the range of 550%-1079% (controlled by external diffusion), ultrasonic power was 150 W and radiation distance was 15 cm. When the dry basis moisture content of carrots (internal diffusion control) was in the range of 40%-125% (controlled by external diffusion), ultrasonic power was 150 W and radiation distance was 15 cm, the average drying rate (2.83 %/min) increased 150.44% than that without ultrasound. This is mainly related to ultrasonic energy attenuation and ultrasonic propagation distance. According to ultrasound energy attenuation equation:

$$I = I_0 e^{-2ax} \tag{6}$$

where, I is acoustic intensity of ultrasound transmitting distance of x, W/cm^2; I_0 is initial ultrasound intensity (W/cm^2); α is attenuation coefficient, dB/m; x is propagation distance, m.

Ultrasound intensity is inversely proportional to ultrasonic propagation distance. In other words, ultrasonic intensity decays much faster at a longer ultrasonic radiation distance. For example, with 21 kHz ultrasound wave, when the ultrasonic radiation distance is 10 cm, sound intensity and sound power in air have a remarkable reduction of more than 20%, while reduced by more than 60% when the distance is 25 cm. In the process of ultrasound assisted hot air drying, the closer ultrasonic radiation distance contributes was, the smaller loss of ultrasonic energy and better reinforcing effect were. Because of the limit of air intake size of this equipment, the distance of ultrasonic radiation can not infinitely close to, 15 cm is the closest distance in the actual drying process.

3.3 Influence of air velocity on the drying characteristics

Effects of air velocity on the drying curve and drying rate curve of carrot slices were studied. The ultrasonic power, drying temperature, ultrasonic radiation distance were 150 W, 40ºC and 15 cm, respectively. The results are shown in Figures 6 and 7, respectively.

It was shown that the strengthening effect of ultrasound reduced with the increase of air velocity in Figure 6. At lower air speeds (≤1.0 m/s), the strengthening effect of ultrasound was more obvious. However, when the air speed was higher than 1.5 m/s, there was a weak strengthening effect of ultrasound. When the air speed was 0.5 m/s, the drying time of carrot slices was shortened to 230 min, 20.69% less than the time that without ultrasound. When the air speed was 1.5 m/s, the drying time of carrot slices was shortened to 160 min and had a reduction ratio of 11.11%. Drying rates of carrot slices under different air velocities were shown in Figure 7. The effect of ultrasound on drying rate of carrots during constant rate (or falling-rate) stage was more obvious. This phenomenon can be explained by the influence of air velocity on ultrasonic wave. The small-scale nonuniformity of air velocity increased with the increase of air velocity, which resulted in the scattering of some ultrasonic wave and the attenuation of ultrasonic wave in original propagation direction. The attenuation is closely related to the state of air turbulence. The greater air speed would lead to a stronger turbulence and faster attenuation of ultrasound energy. Acoustic attenuation and molecular attenuation are of the same order of magnitude with strong turbulence and the attenuation would be more obvious due to the high frequency ultrasound and strong acoustic scattering[16].

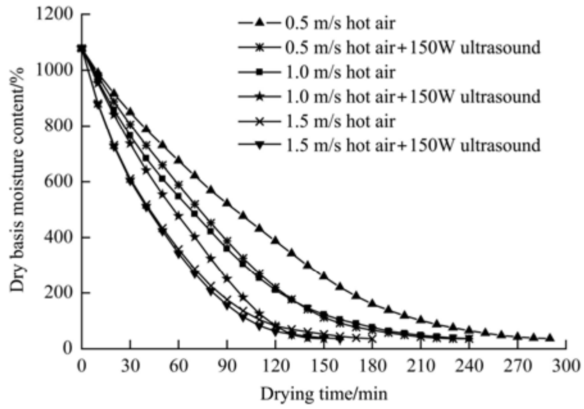


Figure 6 Effect of air velocity on ultrasound combined hot-air drying carrot slices

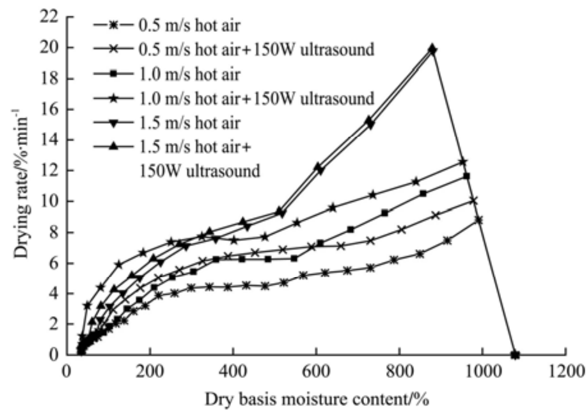


Figure 7 Drying rates of carrot slices under different air velocities

3.4 Influence of temperature on the drying characteristics

Ultrasonic power, air velocity, ultrasonic radiation distance and carrot slices were set at 150 W, 1.0 m/s, 15 cm and 0.3 cm, respectively. The effect of temperature on the drying curve and drying rate curve of carrot slices was studied (Figures 8, 9).

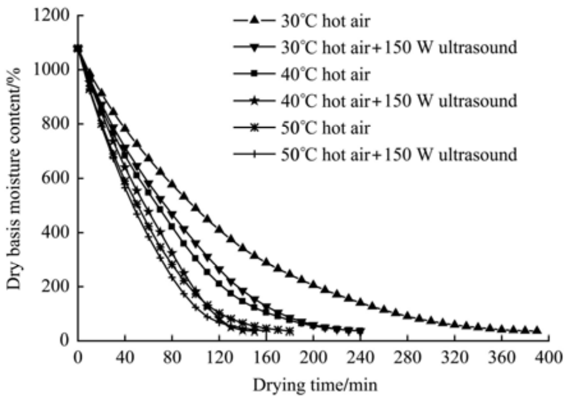


Figure 8 Effect of temperature on ultrasound combined hot-air drying carrot slices

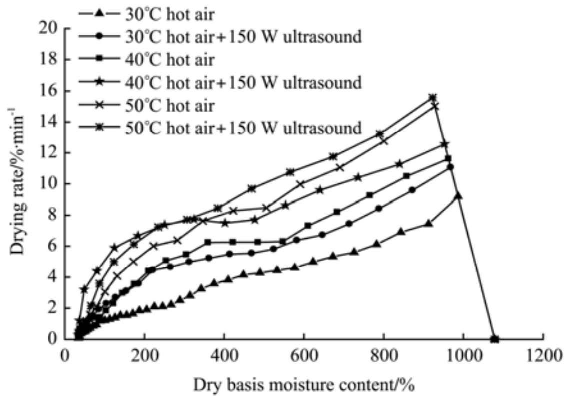


Figure 9 Drying rates of carrot slices under different temperatures

It was referred in Figure 8 that the reinforcing effect of ultrasound attenuation became weak as the temperature increased. In other words, the strengthening effect was more obvious at a lower temperature. The drying time of carrot slices with ultrasound was shortened from 400 min to 240 min at 30ºC, reducing by 40.0%. At the same time, the reduction of drying time was 37.5% and 11.11% at 40ºC and 50ºC, respectively. As shown in Figure 9, the drying rate of carrot slices with ultrasound application increased more significantly at lower temperatures. For example, the drying efficiency of carrots using ultrasound assisted hot-air at 40ºC was even higher than that at 50ºC. This phenomenon was more obvious in the later drying stage (falling-rate stage), which may be attributed to two aspects: (1) a rapid water loss rate of carrot slices will cause a fast shrinkage of appearance at higher temperatures, easily leading to the collapse of internal organizations and the blocking of capillary pores, which weakens the volatility effect generated by ultrasound and increases the attenuation of acoustic energy[17]. (2) air density and the value of acoustic impedance will decrease significantly at higher temperatures, which is adverse to the best match between ultrasound and air. For example, corresponding acoustic impedance is 413.5 Pa·s/m at 20ºC, but it reduces to 380.3 Pa·s/m at 80ºC. Although the device has the function of automatic frequency tracking and signal feedback, it takes effect at a certain range. When the temperature was above a certain value, the coupling efficient would decrease and a large amount of ultrasonic energy would disappear in the form of internal heat loss rather than be emitted in the form of acoustic wave. At the same time, the stability of the device would decrease. Ultrasonic wave has an evident advantage at lower drying temperature because the quite partial energy of water evaporation needed is from ultrasound. While at higher drying temperatures, hot air can provide most of the energy of water evaporation needed. Therefore, the energy provided by ultrasound on the drying process seems not significant at higher drying temperatures.

3.5 Model validation experiments

Since M_e is relatively small to M_t and M_0, it is usually negligible in engineering applications. The Equation (3) calculated moisture ratio of material can be simplified as follows:

$$MR = \frac{M_t}{M_0} \tag{7}$$

Plot relational figures of ln (−ln MR)-ln t for each single factor experiment as were shown in Figures 10-13, both ln (−ln MR) and ln t presented a very good linear relationship and R^2 of all the tests were in the range of 0.9813-0.9962, demonstrating that the relationship between them could be formulated by the linear equation. Thus, the following linear equation can be used:

$$\ln(-\ln MR) = \ln K + n \ln t \tag{8}$$

where, K and n are the parameters.

Squared the above equation twice could obtain Page model as follows:

$$MR = \exp(-Kt^n) \tag{9}$$

It is the model equation that used in this experiment. Page model is an empirical equation that has been used in the drying process modeling of apples, persimmons and sweet potatoes, which has achieved a satisfactory fitting precision[18-20].

3.6 Establishment of model parameters

The results were alternated from ln (−ln MR) to ln t. A linear regression analysis was carried out to predict the values of n, ln K and the linear determination coefficient R_1^2 as shown in Table 1. All the R_1^2 were above 0.98, indicating that the results showed good linearity after transformation.

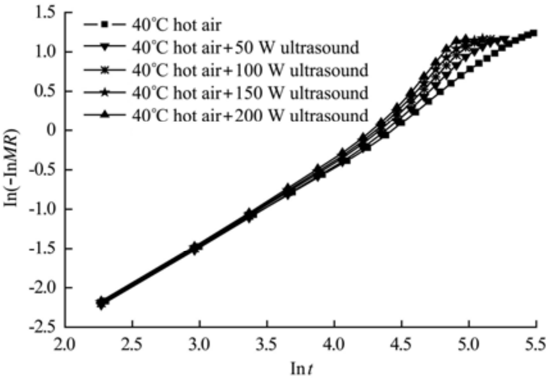


Figure 10 Curves of ln t and ln (−ln MR) at different ultrasound powers

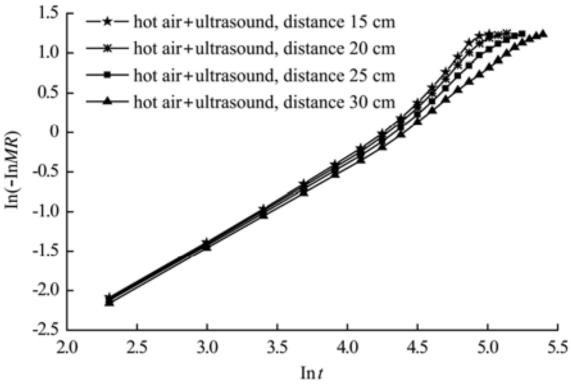


Figure 11 Curves of ln t and ln (−ln MR) at different ultrasonic radiation distances

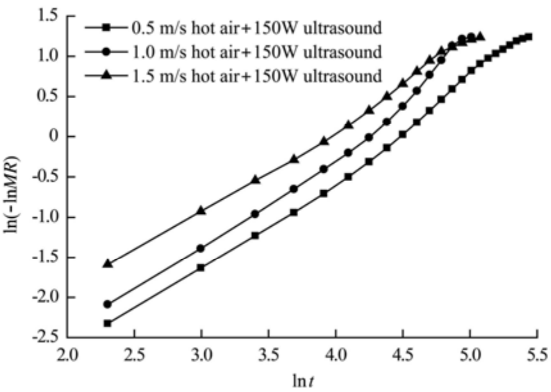


Figure 12 Curves of ln t and ln(−ln MR) at different hot-air velocities

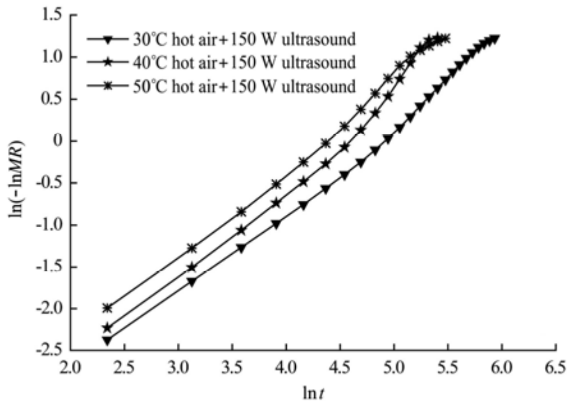


Figure 13 Curves of ln t and ln (−ln MR) at different hot-air temperatures

Table 1 Comparison of the calculated value of model parameters and the measured value

Number	Ultrasonic power	Ultrasonic radiation distance	Air velocity	Temperature	Linear regression parameters and R^2			Comparison of model values with measured values		
					n	K	R_1^2	R_2^2	MBE	$RMSE$
1	0	20	1	30	1.1200	131.2626	0.9962	0.9954	-0.00232	0.005897
2	50	20	1	30	1.1962	161.1604	0.9907	0.9901	0.01012	0.012561
3	100	20	1	30	1.2281	173.1399	0.9877	0.9962	-0.00176	0.004334
4	150	20	1	30	1.2510	182.4908	0.9858	0.9884	0.008299	0.010328
5	200	20	1	30	1.2701	189.1802	0.9813	0.9956	-0.00175	0.005104
6	150	15	1	40	1.2709	189.0478	0.9813	0.9935	-0.00602	0.007081
7	150	20	1	40	1.2506	182.3449	0.9857	0.9924	-0.00756	0.008879
8	150	25	1	40	1.2053	162.9592	0.9902	0.9912	0.008306	0.009342
9	150	30	1	40	1.1457	140.9493	0.9951	0.9932	0.005167	0.00744
10	0	15	0	40	1.1600	221.9606	0.9891	0.9885	0.008485	0.010681
11	0	15	1	40	1.1200	131.2626	0.9962	0.9921	0.004926	0.00754
12	0	15	1.5	40	1.0249	56.16535	0.9964	0.9964	-0.00532	0.008649
13	150	15	0	40	1.2119	206.6239	0.9922	0.9926	-0.00167	0.005823
14	150	15	1.5	40	1.0709	64.0523	0.9944	0.9947	-0.00165	0.005825
15	150	15	1	30	1.1373	154.4855	0.9915	0.9910	0.005227	0.008188
16	150	15	1	50	1.1780	110.2224	0.9942	0.9913	-0.00826	0.009874

The values of n and $\ln K$ were fitted using DPS software and non-significant items were excluded. The fitting equation of model parameters was as follows:

$$n = 2.1132 - 0.0255X_1 + 0.2104X_3 + 0.0473X_4 - 3.52\times10^{-6}X_1^2 - 7.31\times10^{-4}X_2^2 - 0.2053X_3^2 - 8.16\times10^{-4}X_4^2 + 7.93\times10^{-4}X_1X_2 + 7.39\times10^{-5}X_1X_3 + 3.65\times10^{-4}X_1X_4 - 0.0023X_2X_4$$

$$(R^2=0.9758) \quad (10)$$

$$K = -604.43 - 0.42X_1 + 23.95X_2 + 35.22X_4 - 0.0014X_1^2 - 0.343X_2^2 - 98.76X_3^2 - 0.39X_4^2 + 0.04X_1X_2 + 0.16X_1X_3 + 2.23X_2X_3 - 0.47X_2X_4$$

$$(R^2=0.9825) \quad (11)$$

MR changes of every research group were calculated using the obtained mathematical model, and the model values were compared with measured values. The results were shown in Table 1. Most of the R_2^2 were all above 0.99, and all the MBE and most of the RMSE were below 0.01. Therefore, all test indicators of the model could meet the accuracy requirements, which showed that the model can fit the experimental values better.

4 Conclusions

Conventional hot air drying is still widely used in many fields due to simple, low-priced and easily controlled equipment. However, it is controlled by internal diffusion of water in mid- and late-drying process, which results in a low heat and mass transfer efficiency. How to improve the internal diffusion-controlled heat and mass transfer coefficient is becoming important. Compared to hot-air drying, hot-air drying coupled with power ultrasound can produce high-frequency vibration and great acceleration of air medium, enhancing fluid turbulence and micro-jet and reducing the thickness of heat and mass transfer boundary surface. Moreover, the ultrasonic energy absorbed by liquid medium (water) is much than by gas medium, which accelerates the process of gaseous diffusion of water in materials. Ultrasound can not only change structure properties of materials but also strengthen heat and mass transfer in hot air drying.

The results of ultrasonic assisted hot air drying of carrot slices showed that drying rate of carrot slices increased with the increase of ultrasound power and the decrease of radiation distance. Power ultrasound had a greater reinforcement effect on hot-air drying at lower air velocities and temperatures. The drying time of ultrasound assisted hot-air drying reduced by 37.5% compared to the hot-air drying with 150 W, 15 cm (radiation distance), 1.0 m/s and 40°C. The Page equation can be applied to describe the process of the ultrasound assisted hot-air drying of the carrot slices.

Acknowledgements

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (11004049) and Science and Technology Innovation Team of Henan University of Science and Technology.

[References]

[1] Figiel A . Drying kinetics and quality of vacuum-microwave dehydrated garlic cloves and slices. Journal of Food Engineering, 2009; 94(1): 98−104.

[2] Wu H H, Han Q H, Yang B N, Zhao D L, Li Y F, Bai L F. Experiment on Combining hot air and microwave vacuum to dry lyeium. Transactions of the CSAM, 2010; 41(Z1): 178−181. (in Chinese with English abstract)

[3] Wanyo P, Siriamornpun S, Meeso N. Improvement of quality and antioxidant properties of dried mulberry leaves with combined far-infraredradiation and air convection in Thai tea process. Food and Bioproducts Processing, 2011; 89(1): 22−30.

[4] Hande A R, Swami S B, Thakor N J. Effect of drying methods and packaging materials on quality parameters of stored kokum rind. Int J Agric & Biol Eng, 2014, 7(4): 114−126.

[5] Boonkird S, Phisalaphong C, Phisalaphong M. Ultrasound-assisted extraction of capsaicinoids from Capsicum frutescens on a lab- and pilot-plant scale. Ultrasonics Sonochemistry, 2008; 15(6): 1075−1079.

[6] Fernandes F A N, Oliveira I P, Rodrigues S. Use of ultrasound for dehydration of papayas. Food Bioprocess Technology, 2008; 1(4): 339−345.

[7] Bizkarguenaga E, Iparragirre A, Zabaleta I, Vallego A, Fernández L A, Prieto A, et al. Focused ultrasound assisted extraction for the determination of PBDEs in vegetables and amended soil. Talanta, 2014; 119(15): 53−59.

[8] Yao Y, Zhang W J, Yang K, Liu S Q, He B X. Theoretical model on the heat and mass transfer in silica gel packed beds

during the regeneration assisted by high-intensity ultrasound. International Journal of Heat and Mass Transfer, 2012; 55(23-24): 7133−7143. (in Chinese with English abstract)

[9] Sun B Z, Jiang R Q, Huai X L, Li B, Liu D Y. Enhancing osmotic dehydration with acoustic cavitation. Journal of Chemical Industry and Engineering, 2004; 55(10): 4−8. (in Chinese with English abstract)

[10] Dong H X, Xiang Y L, Wang S S, Sun Z S. Transfer rule of osmotic dehydration of carrots under ultrasound treatment. Journal of Harbin Engineering University, 2008; 29(2): 189−193.

[11] Fernandes F A N, Linhares Jr F E, Rodrigues S. Ultrasound as pre-treatment for drying of pineapple. Ultrasonics Sonochemistry, 2008; 15(6): 1049−1054.

[12] Nowacka M, Wiktor A, Śledź M, Jurek N, Witrowa-Rajchert D. Drying of ultrasound pretreated apple and its selected physical properties. Journal of Food Engineering, 2012; 113(3): 427−433.

[13] García-Péreaz J V, Cárcel J A, Benedito J, Mulet A. Power ultrasound mass transfer enhancement in food drying. Trans IChemE, Part C, Food and Bioproducts Processing, 2007; 85(3): 247−254. (in Chinese with English abstract)

[14] Duan X, Liu W, Ren G Y, Liu W C, Liu Y H. Comparative study on the effects and efficiencies of three sublimation drying methods for mushrooms. Int J Agric & Biol Eng, 2015, 8(1): 92−99.

[15] Ortuño C, Pérez-Munuera I, Puig A, Riera E, Garcia-perez J V. Influence of power ultrasound application on mass transport and microstructure of orange peel during hot air drying. Physics Procedia, 2010; 3 (1): 153−159.

[16] Cheng D. Study on propagation properties of sound in wind and temperature fields. Beijing: National University of Defense Technology, 2009: 11−12.

[17] Guan Z Q, Wang X Z, Li M, Jiang X Q, Xie J. Mathematical modeling of hot air drying of thin layer Litchi flesh. Transactions of the CSAM, 2012; 43(2): 151−158.

[18] Kaleta A, Górnicki K, Winiczenko R, Chojnacka A. Evaluation of drying models of apple (var. Ligol) dried in a fluidized bed dryer. Energy Conversion and Management, 2013; 67(3): 179−185.

[19] Doymaz İ. Evaluation of some thin-layer drying models of persimmon slices (Diospyros kaki L.). Energy Conversion and Management, 2012; 56(4): 199−205.

[20] Singh N J, Pandey R K. Convective air drying characteristics of sweet potato cube (Ipomoea batatas L.). Food and Bioproducts Processing, 2012; 90(2): 317−322.