

Microwave intermittent drying enhances drying kinetics of banana slices

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Abstract. Microwave intermittent drying kinetics of banana slices were investigated under different power levels (250, 400, 550 and 700W), sample thickness (3, 6, 9 and 12mm), heating time (11, 14, 17 and 20s) and intermittent time (50, 60, 70 and 80s) during each cycle. Results indicated that all the four factors had significant influence on the drying kinetics, whereas microwave power gave the most significant effect, followed by heating/intermittent time and sample thickness. Drying rate curves illustrated that the drying process of banana slices contained the increasing rate period. Moisture effective diffusivity was advanced with the growth of power level, thickness and heating time. The whole drying time was added with the increase of the intermittent time. When the drying parameters of banana slices changed under the conditions, the moisture effective diffusion coefficient varied from 2.10×10^{-10} to $7.83 \times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$.

Introduction

Banana is one of famous fruits in southern China, which tastes sweet and delicious. It is also multi-function health product, including promoting gastrointestinal peristalsis, soothing nerves, etc. Nowadays, banana is widely planted in China, and the total export production had got 12, 899 thousand tons in 2014^[1, 2].

Due to both seasonal and perishable nature characteristics, it is difficult to keep the fruit long-term preservation with its strong respiratory intensity. According to the research^[3, 4], the loss rate of banana reaches up to 20%-30%. As a result, choosing the efficient storage way for the banana products has become the most important part of the whole processing industrial chain. Drying is one of the most common methods used for banana processing and extending their shelf lives by reducing the moisture content to a low level, which prevents the growth and reproduction of microorganisms and minimize many of the moisture-mediated deteriorative reactions.

Microwave intermittent drying technology is based on the common microwave drying technology while controlling heating time and interval time accurately. Differ to other ways of drying, microwave intermittent drying technology depending on its special heating quality, rapid drying rate and less heating time has become more and more popular. Nowadays, much research has been carried out to investigate the characteristics of microwave intermittent drying technology, especially about litchi, longan, potato, carrot and ginger etc. However, the research about banana slices drying kinetics under the above way dates few^[5-7]. In this paper, the objectives of current work were to focus on microwave intermittent drying kinetics of banana slices.

Materials and methods

Raw material

Fresh bananas were purchased from a local market in Ya'an, Sichuan province of PR China. Bananas of uniform size were selected and stored at 4 °C before experiments. The average radius of the samples was about 26 mm. The initial moisture content of bananas was $4.68 \text{ kg} \cdot \text{kg}^{-1}$ in dry basis, as determined by the AOAC method no. 934.06.

Experimental set-up and procedure

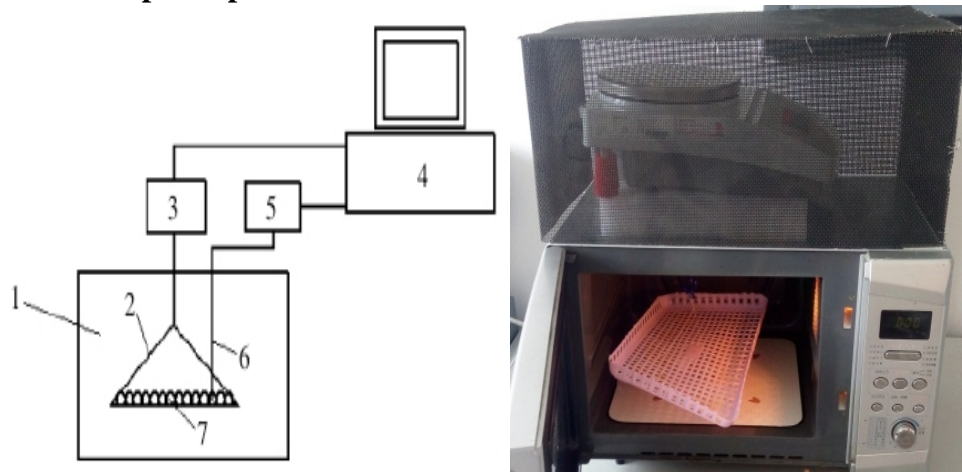


Fig. 1 The structure of microwave intermittent drying equipment

A schematic diagram of equipment used for microwave intermittent drying is shown in Fig. 1. This apparatus basically consist of microwave generator inside the drying chamber to heat the sample, an electronic weighing equipment linked with charging tray to realize automatic weighing, and a Proportional-Integral-Derivative (PID) controller (Omron, model E5CN, Tokyo, Japan) to control drying transmitting power. After the dryer had reached steady conditions for the set points, the banana slices were spread into a single layer onto a silicone rubber tray. As shown in Table 1, the drying experiments were carried out at different transmitting powers (250, 400, 550 and 700W), heating time (11, 14, 17 and 20s) and intermittent time (50, 60, 70 and 80s) during each cycle on the drying characteristics and quality of banana slices. Drying was continued until the samples reached the desired final moisture content of $0.17 \text{ kg} \cdot \text{kg}^{-1}$ in dry basis. The product was cooled and packed in low density polyethylene bags that were heat sealed. The experiments were performed in triplicate.

Table 1 Design for experiments with drying parameters included

N o.	Slice thickness (mm)	Microwave power (W)	Heating time (s)	Intermittent time (s)
1	6	250	14	80
2	6	400	14	80
3	6	550	14	80
4	6	700	14	80
5	3	400	11	80
6	6	400	11	80
7	9	400	11	80
8	12	400	11	80
9	12	250	11	80
10	12	250	14	80
11	12	250	17	80
12	12	250	20	80
13	3	250	11	50
14	3	250	11	60
15	3	250	11	70
16	3	250	11	80

Calculation of moisture effective diffusivity

The moisture ratio (MR) of banana slices during drying experiments was calculated with a more simplified form as follows^[8]:

$$MR = \frac{M_t}{M_o} \quad (1)$$

Where M_0 is the initial moisture content of banana slices, M_t is the moisture content at time t .

The drying rate of sample slices during drying experiments was computed using Eq. (2)^[9]:

$$DR = \frac{M_{t_1} - M_{t_2}}{t_2 - t_1} \quad (2)$$

Where t_1 and t_2 is the drying time at different moment respectively during drying with expression in hours; M_{t_1} and M_{t_2} is the moisture content of samples at t_1 and t_2 , $g \cdot g^{-1}$.

The calculation of moisture effective diffusivity was determined as shown in Eq. (3)^[10-15]:

$$\ln(MR) = \ln\left(\frac{6}{p^2}\right) - (p^2 \frac{D_{eff} t}{r_o^2}) \quad (3)$$

There is a linear relationship between the natural logarithm of moisture ratio and drying time of sample slices according to Eq. (3). So the slope can be given from the linear regression of $\ln(MR)$ versus time curves, then the effective diffusion coefficient (D_{eff}) can be determined.

Results and discussion

Effect of microwave power on drying kinetics of banana slices

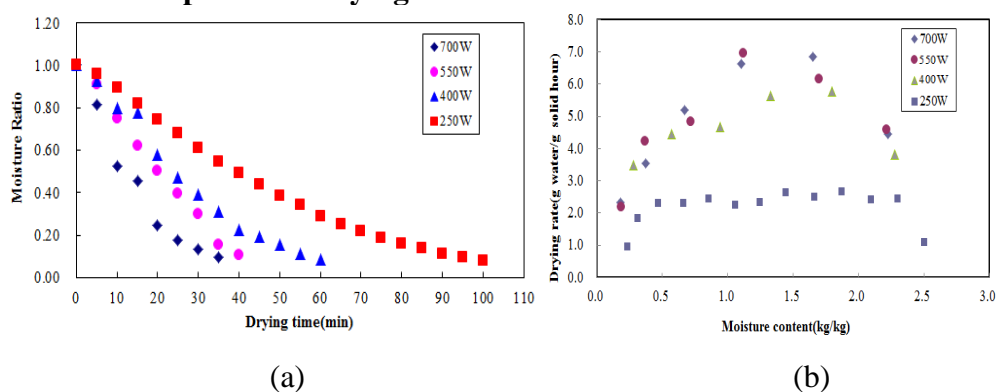


Fig. 2 Drying kinetics of banana slices at different microwave power level with the heating/intermittent time of 14s/80s and slices thickness of 6mm

To compare the effect of different microwave power (250, 400, 550 and 700W) on the drying kinetics of banana slices, the curves of MR versus drying time and curves of drying rate versus moisture content were shown in Fig. 2. It can be seen that the drying time to reach the desired moisture content was approximately 100, 60, 40 and 35min with a constant slice thickness of 6mm at microwave power of 250, 400, 550 and 700W, respectively. The results confirmed that the drying rate was significantly enhanced with the growth of power level. From Fig. 2b, there contained three stages during the drying of banana slices: accelerated drying stage, constant drying stage and decelerated drying stage. And the constant drying stage gradually drawdown as the increase of microwave power. It is clear that diffusion is the dominant physical mechanism governing moisture movement from interior to surface of banana slices during drying process. Similar results have been reported in literature by other researchers, such as Monukka seedless and American ginseng slices.

Effect of slice thickness on drying kinetics of banana samples

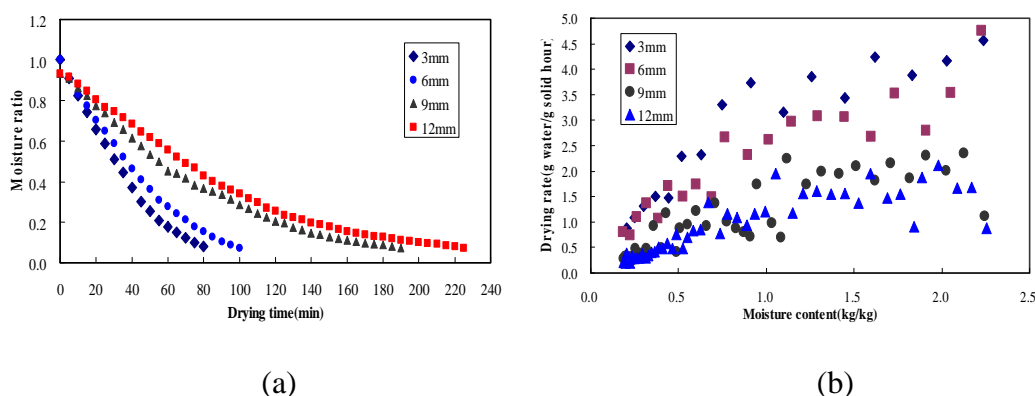


Fig. 3 Drying kinetics of banana slices at different slices thickness with the heating/intermittent time of 11s/80s and the microwave power of 400W

Under the drying condition with the microwave power of 400W and the heating/intermittent time of 11s/80s, the drying curves of banana slices with different thickness levels were investigated. Fig. 3a showed that the greater the thickness, the longer the heating time. Generally compared to the variation trend of the curves, it was found that the heating time did not prolong in proportion as the thickness of banana slices increased. The moisture content of 9mm banana slice fell slowdown significantly. This might be because the thickness level was at a relatively high value and the microwave can not reach into the center of the banana slices, which lead to the extension of whole drying time.

As shown in Fig. 3b, it presented drastic fluctuations during the subsequent drying process from 3 to 12mm. Before the inflection point, the power level had a great impact on banana slices. The stronger the power level, the more moisture diffusion would occur. After the point, the drying rate of banana slices with different thickness fluctuated along with the drying process.

Effect of heating time on drying kinetics of banana slices

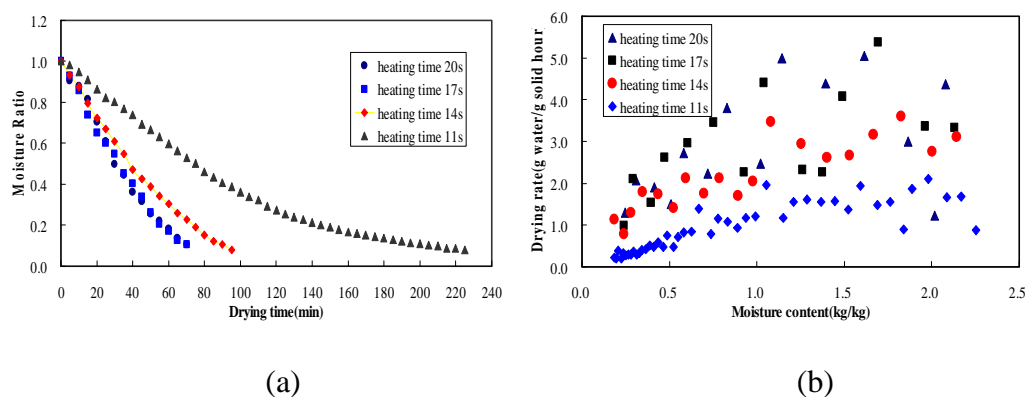


Fig. 4 Drying kinetics of banana slices at different heating time with the intermittent time of 80s and the microwave power of 250W at 12mm

The effects of heating time during each cycle on the drying kinetics of banana slices were shown in Fig. 4. Based on the preliminary experiment results, the heating time was selected at 11, 14, 17 and 20s, respectively. And this was corresponding to the time of sample increased to 50, 55, 60 and 65°C. From Fig. 4b, the curve demonstrated that the whole drying process with heating time of 11s got the longest time, while heating time of 20s during each cycle took the least. Meanwhile, the whole drying time with the heating time of 17s and 20s were almost the same. When the temperature inside the samples increased to a certain value, parts of the microwave power would transfer from the internal structure, resulting in the energy loss.

Effect of intermittent time on drying kinetics of banana samples

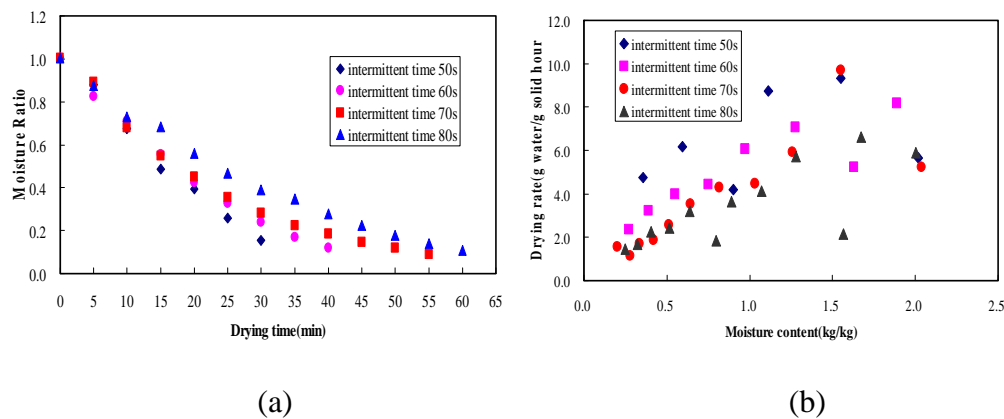


Fig. 5 Drying kinetics of banana slices at different intermittent time with the intermittent time of 11s and the microwave power of 250W at 3mm

During the banana slices with 3mm at the intermittent time of 11s and the microwave power of 250W in the whole drying process, the effects of different intermittent time level on the drying kinetics were investigated. The results showed that the whole drying time increased along with the intermittent time level. It might be due to the reason that the heat energy dissipated during the intermittent time. From Fig. 5b, it can also be seen that the drying curve with intermittent time of 50s showed almost linear variation trend, while the curve at higher level presented a trend of fluctuating downward and contained twists and turning points. It might be because the interval period was coherent and the internal temperature can be maintained within a certain period of time, so that the moisture diffusion rate was relatively stable.

Analysis of moisture effective diffusivity under different conditions

Table 2 Moisture effective diffusion coefficients under different drying condition

No.	condition		Linear regression fitting formula	R ²	D _{eff} (10 ⁻¹⁰ m ² ·s ⁻¹)
1	Microwave power (W)	250	lnMR = -0.0257x + 0.2179	0.983	15.62
2		400	lnMR = -0.0422x + 0.2208	0.9821	25.65
3		550	lnMR = -0.055x + 0.2377	0.9388	33.43
4		700	lnMR = -0.0698x + 0.0823	0.9895	42.43
5	Slice thickness (mm)	3	lnMR = -0.0138t + 0.01762	0.9878	2.10
6		6	lnMR = -0.0257t + 0.1678	0.9847	15.62
7		9	lnMR = -0.0127t + 0.086	0.9976	17.37
8		12	lnMR = -0.0109t + 0.0925	0.9974	26.50
9	Heating time (s)	11	lnMR = -0.0117t + 0.1276	0.9974	28.46
10		14	lnMR = -0.0257t + 0.204	0.9726	62.51
11		17	lnMR = -0.0322t + 0.2035	0.9686	78.32
12		20	lnMR = -0.032t + 0.2041	0.9776	77.81
13	Intermittent time (s)	50	lnMR = -0.0543t + 0.0932	0.9809	8.25
14		60	lnMR = -0.0533t + 0.1299	0.9853	8.10
15		70	lnMR = -0.0443t + 0.0631	0.9981	6.73
16		80	lnMR = -0.0365t + 0.1053	0.9885	5.55

As shown in Table 2, the moisture effective diffusion coefficient (D_{eff}) of the samples increased from 15.62×10^{-10} to $42.43 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ as the microwave power level increased from 250 to 700W. It was found that the D_{eff} values of the samples varied from 2.10×10^{-10} to $26.50 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ when banana slices thickness increased from 3 to 12mm. It indicated that increasing the thickness could increase the moisture effective diffusion coefficient. Meanwhile, it was observed that the moisture effective diffusion coefficient at different heating times was between 28.46×10^{-10} and $78.32 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$. The D_{eff} values at different interval periods varied from 5.55×10^{-10} to $8.25 \times 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$, which were significantly less than other variation factors. The D_{eff} values between 50s and 60s were almost

the same. And the intermittent time at 50s was 1.48 times compared to the 80s, indicating that reduce the intermittent time had beneficial effect on improving the drying rate.

Conclusions

The effect of heating time, intermittent time, slice thickness and power level on the kinetics of banana slices were examined in this investigation. All of the above parameters had significant impact on the drying rate. And the moisture effective diffusion coefficient was related to power level, heating/intermittent time, except the slice thickness.

During the whole drying process of banana slices under different microwave power level, it contained accelerated drying stage, constant drying stage and decelerated drying stage. An inflection point existed during the slice thickness varied from 9mm to 12mm. The whole drying time was added with the increase of the intermittent time. When the drying parameters of banana slices changed under the conditions, the moisture effective diffusion coefficient varied from 2.10×10^{-10} to $7.83 \times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$.

Acknowledgements

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