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Drying of Papaya (*Carica papaya L.*) using a Microwave-vacuum Dryer

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***Abstract*—**In present work, drying characteristics of fresh papaya (*Carica papaya L.*) was studied to understand the dehydration process and its behavior. Drying experiments were carried out by a laboratory scaled microwave-vacuum oven. The parameters affecting drying characteristics including operating modes (continuous, pulsed), microwave power (400 and 800 W), and vacuum pressure (20, 30, and 40 cmHg) were investigated. For pulsed mode, two levels of power-off time (60 and 120 s) were used while the power-on time was fixed at 60 s and the vacuum pressure was fixed at 40 cmHg. For both operating modes, the effects of drying conditions on drying time, drying rate, and effective diffusivity were investigated. The results showed high microwave power, high vacuum, and pulsed mode of 60 s-on/60 s-off favored drying rate as shown by the shorten drying time and increased effective diffusivity. The drying characteristics were then described by Page's model, which showed a good agreement with experimental data.

***Keywords*—**papaya, microwave-vacuum drying, effective diffusivity, Page's model

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I. INTRODUCTION

PAPAYA (Carica papaya L.) is one of the tropical fruits with a fast-growing market because of its luscious taste. Papayas are rich sources of antioxidant nutrients, bioflavonoids, minerals, digestive enzyme, and fibers. The growing demand for such healthy diets results in increasing demand for fresh, processed and semi-processed papayas. Because papayas are seasonal fruits with a short shelf-life, it is challenging to develop a process for prolonging the shelf-life of the final products. One of value-adding methods to papayas is drying to produce dried products in forms of cubes, chips, strips, etc.

Drying is a food-preservation method for water removal to improve the quality and durability of foodstuffs [1]. Though conventional dehydration processes including hot-air drying, sun drying, and freeze drying are widely used for food industries, they have disadvantages in terms of low energy efficiency, thermal degradation, and nutrient loss of finished products [2]. These problems were controlled by an application of microwave-vacuum drying technique since it combines advantages of microwave heating, i.e. saving time and energy [3,4] and vacuum condition, i.e. lower boiling-point temperature and increased rate of evaporation. This technique was successfully applied to numerous food products such as canberies [4], mint [5], lactose powder [6], garlic [7], and pumpkin [8].

A good understanding of the drying kinetics and the effect of drying parameters are necessary for a design and control of the drying process to achieve the desired quality of products. Although several researchers studied the drying kinetics of various products [7-10], no data on the drying kinetics of papaya using a microwave-vacuum technique were available.

Therefore, the objective of this study was to evaluate the effects of drying parameters including operating modes, microwave power levels, vacuum pressure, and power-off times on the drying kinetics of papaya and the effective moisture diffusivity. The experimental results were also correlated with an empirical drying model.

II. EXPERIMENTAL

A. Materials

Fresh papayas (*Carica papaya L.*) of similar maturity (7.8-8.0 °Brix) were purchased from a local fruit market in Nonthaburi, Thailand. Prior to the test, they were washed, hand-peeled, and cut into cubic shape (1.5 cm x 1.5 cm x 1.5 cm) using a stainless steel cutter. Initial moisture content was obtained from drying a papaya cube in an oven (Memmert U 40) at 105 °C for 24 hours.

B. Drying equipment and experimental procedure

A programmable domestic microwave oven (Elextrolux Model KOR-8667 Model KOR-8667, 900 W Maximum output at 2450 Hz) was set up with an internally sealed drying chamber. The drying chamber was connected with a vacuum pump (Edwards High Vacuum International Model RV8) to create vacuum pressures of 20, 30, and 40 cmHg. In this study, two levels of microwave powers were 400 and 800 W. The measurement of the power output was conducted by the standard procedure described by Cui et al. [11]. For a pulsed mode, the magnetron was alternately turned on and off corresponding to two pulsation periods: 60s-on/60s-off, 60s power-on time and 60 s power-off time, and 60s-on/120s-off, 60 s power-on time and 120s power-off time. Ten papaya cubes were uniformly spread on a glass turnable inside the drying chamber for an even absorption of microwave energy. The drying sample was removed from the drying chamber at the end of power–off time and weighted by a digital balance for calculation of moisture loss [4,10]. Each weighting process was conducted within 20 seconds during the drying process. The reproducibility of the measurement and experiments was within the range of ±5%.

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C. Drying characteristics and model

To study drying characteristics of fresh papaya using the microwave-vacuum drying, the moisture ratio (MR) and drying rate of papaya were calculated using the following equations:

$$\mathrm{MR} = \frac{\mathrm{M_t - M_e}}{\mathrm{M_0 - M_e}} \tag{1}$$

$$\text{Drying rate} = \frac{\mathrm{M_{t+\Delta t} - M_t}}{\Delta \mathrm{t}} \tag{2}$$

where M_t is the moisture content (g of water/g of dry basis) at time t, M_e is the equilibrium moisture content (g of water/g of dry basis), M_0 is the initial moisture content (g of water/ g of dry basis), which was assumed to be zero [6, 10, 12]. M_{t+dt} is the moisture content (g of water/g of dry basis) at time t+dt, and t is the time interval.

In this study, Fick's second law of diffusion was used to express the drying process during the first falling-rate period. Assuming a constant diffusion coefficient, the differential equation for one-dimensional diffusion [13] is given in equation (3):

$$\frac{\partial M}{\partial t} = D_{eff}\left(\frac{\partial^2 M}{\partial x^2}\right) \tag{3}$$

where M is the moisture content (g of water/g of dry basis), t is the time (s), x is length (m), and D_{eff} is the effective diffusion coefficient (m^2/s), which includes all possible mass transfer mechanisms during drying process [9, 12].

The initial and boundary conditions for a cubic of papaya of thickness 2L are:

$t = 0;\ 0 \le x \le L;\ M = M_0$

$t > 0;\quad x = 0\ ;\ M = M_e$

where M_0 is the initial moisture content (g of water/g of dry basis) at time t=0, M_e is the equilibrium moisture content.

For drying of papaya cubic, if external resistances are assumed to be negligible, the infinite series solution [13] for moisture transport in a cubic geometry is given as:

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\left(\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp(-(2n+1)^2\pi^2 D_{eff}\,\frac{t}{4L^2})\right)^3 \tag{4}$$

From this equation, the effective diffusivity can be obtained from the data of moisture ratio versus time.

For long drying times and unaccomplished moisture ratio, less than 0.6, Equation (4) can be reduced to an empirical form called Page's equation [14]

$$\mathrm{MR} = \frac{\mathrm{M - M_e}}{\mathrm{M_0} - \mathrm{M}_e} = \exp\,(-kt^n) \tag{5}$$

where k is the drying rate constant and n is the Page's parameter.

The coefficient of determination (R^2), reduced chi-square ($\chi 2$), and root mean square error (RMSE) were calculated to determine the fitting ability of the model as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}(\mathrm{MR_{exp,i} - MR_{pre,\,i}})^2}{N-n} \tag{6}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(M_{R,cal,i} - M_{R,\exp,i})^2\right]^{1/2} \tag{7}$$

where $MR_{exp,i}$, $MR_{pre,i}$ are the i^{th} experimental and predicted moisture ratios, respectively, while *N* and *n* are the number of observation and constant in the drying model, respectively.

III. RESULTS AND DISCUSSION

A. Drying characteristics of fresh papaya

The papayas were dried at different conditions in a microwave-vacuum dryer. The papaya cubes of initial moisture content of approximately 8.0 g water per g dry matter were dried to final moisture content of about 0.1 g water per g dry matter. Fig. 1 shows the change of moisture content in a sample versus time under continuous drying at 400 and 800 W and 40 cmHg. As seen from this figure, the moisture content decreases continuously with time. Table 1 shows time required to drying papaya to the final moisture ratio of 0.01 at various conditions. The times required to dry the papaya cubes with the continuous mode at 400 and 800 W were 78.82 and 47.79 minutes, respectively.

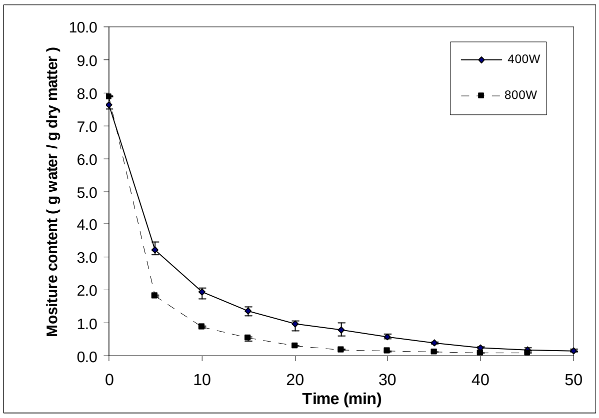

Fig. 1 The change of moisture content in a sample versus time under continuous drying at 400 and 800 W

TABLE I
DRYING TIME REQUIRED TO REDUCE THE MOISTURE RATIO TO 0.01

Drying conditions			Drying time (min)
Power	Vacuum Pressure	Heating Mode	
400 W	20 cmHg	Continuous	134.74 ±5.39
	30 cmHg	Continuous	104.47 ±4.34

	40 cmHg	Continuous	78.72 ±0.34
		60s-on/60s-off	72.63 ±1.82
		60s-on/120s-off	115.47 ±4.17
800 W	20 cmHg	Continuous	90.26 ±3.53
	30 cmHg	Continuous	69.88 ±4.19
	40 cmHg	Continuous	47.79 ±3.24
		60s-on/60s-off	38.21±1.20
		60s-on/120s-off	83.97 ±5.09

B. Effect of microwave power output

Fig. 2 shows the change in moisture ratio versus time for continuous drying at 400 and 800 W. Compared at the same vacuum pressure, the drying rate of papaya cubes apparently depended on the microwave power. At the vacuum pressure of 20 cm Hg, microwave vacuum drying at 400 and 800 W required 134.74 and 90.26 minutes, respectively, for reducing moisture ratio to less than 0.01. The drying rate increased as microwave power increased as a result of higher energy absorption in the drying sample. However, the microwave power absorptivity of the food material depended on mass, geometry, dielectric properties, and position within the drying chamber, it must be cautioned that the microwave power output was not the power absorbed by the papaya cubes [4]. Some of microwave energy absorbed by the food penetrated and converted to heat which increased the product temperature. Heating continued until the temperature reached the boiling point of water, vaporization of moisture within the drying sample occurred as major mass transfer. Since the energy absorbtivity also depended on the moisture content of the sample, the effect of microwave power on drying rate was more pronounced at the early period of drying when the initial moisture was high. At the later period of drying when the moisture was low, less energy would penetrate and heat the product, which resulted in lower rate of drying. The effect of microwave power on drying rate agreed with thethe previous study by Yongsawasdigul and Gunasekaran [4].

C. Effect of vacuum pressure

The effect of vacuum pressure on moisture ratio and drying time were conducted at 20, 30, and 40 cm Hg for each power output. Fig. 2 also shows that the vacuum pressure level had a significant effect on moisture ratio of papaya cubes. An increase in vacuum pressure resulted in a decrease in drying time. At 800W and continuous heating mode, the drying times required for decreasing the moisture ratio to 0.01 were 90.26, 69.88, and 47.79 minutes at the vacuum pressure of 20, 30, and 40 cmHg, respectively. The same trend was also observed for the power output of 400W. As higher vacuum pressure resulted in lower boiling point of water, operating at higher vacuum pressure allowed higher evaporation rate than that of low pressure. This was because water removal from the sample during drying process was accelerated by a pressure gradient between partial vapor pressure within the sample and the ambient pressure [4]. The results were in agreement with a study by Yongsawasdigul and Gunasekaran [4] that drying at lower pressure (absolute) caused less reflection of microwave, and hence, higher drying efficiency.

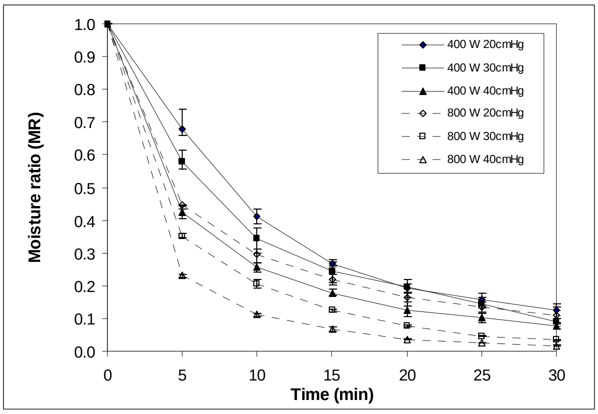

Fig. 2 Effect of microwave power output and vacuum pressure on continuous drying at 400 and 800 W

D.Effect of power-off time

Since supplying microwave energy continuously leads to damage of the product due to excessive heating, pulsed-mode heating was developed to overcome such problem by setting the microwave power cycle of given on- and off-times [4]. The effect of power-off time on the drying of papaya cubes using the microwave vacuum dryer was shown in Fig. 3. In this experiment, the drying was performed in the pulsed mode with a fixed power-on time (60s) and two power-off times (60 and 120 s). Compared to a continuous mode, microwave vacuum drying experiment performing in the pulsed mode of 60s-on/60s-off showed higher drying rate while that of 60s-on/120s-off showed an adverse effect on drying performance. At the microwave power of 800 W, the time required to reduce the moisture ratio of papaya cubes to less than 0.01 for continuous mode, pulsed mode of 60s-on/60s-off, and pulsed mode of 60s-on/120s-off were 47.79, 38.21, and 83.97 minutes, respectively, The same trend was also observed for the microwave power of 400W. The faster decrease in moisture ratio and drying rate for the pulsed mode drying was resulted from two mechanisms of water removal during drying process: evaporation and diffusion. The former occurred during the power-on time while the latter occurred within the sample during the power-off time. The power-off time of 60 s allowed the internal moisture to redistribute, which accelerated the drying rate [4]. Compared to the continuous drying mode, the pulsed mode drying of 60s-on/120s-off showed an adverse effect because a long power-off time led to energy loss and required additional energy to increase the product temperature to reach the boiling point for the next cycle. The long power-off time also resulted in lower energy efficiency as reported by a previous study [4]

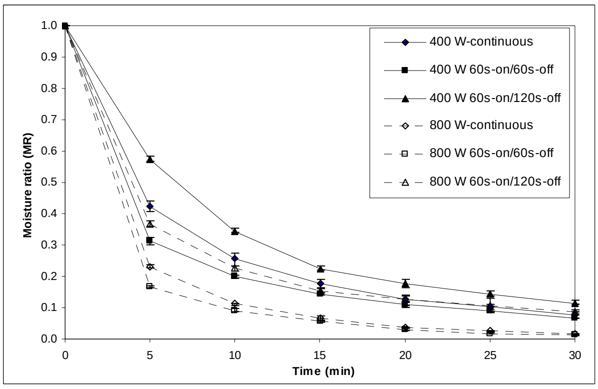

Fig. 3 Effect of power-off time on drying process of fresh papaya at various drying conditions

E. Effective diffusivity

Table II shows the values of effective diffusivity (D_{eff}) at various drying conditions. The values of effective diffusivity of papaya cubes at microwave power of 400 and 800W varied in the range of 0.506×10^{-8} -0.767×10^{-8} m^2/s and 0.703×10^{-8} -1.356×10^{-8} m^2/s, respectively. For the same vacuum pressure level and mode of operation, the D_{eff} values of 800W were higher than those of 400 W. The D_{eff} values increased progressively as the vacuum pressure increases. As mentioned earlier, both microwave power and vacuum pressure favored the mass transfer of moisture, the results from the determination of the D_{eff} values support the results in the prior sections that higher power resulted in higher drying rate. At drying condition of 800 W and 40cmHg, pulsed mode of 60s-on/60s-off showed the highest value of D_{eff}, followed by the continuous mode, and pulsed mode of 60s-on/120s-off, respectively. This result was in agreement with the previous section that higher D_{eff} resulted in increased rate of drying. Compared to the D_{eff} values reported by El-Aouar et al. [1], microwave vacuum drying showed an improved drying rate than hot-air drying.

F. Drying model

Based on Page's model, the change of moisture ratio with drying time can be predicted from Equation (5). Figure 4 shows the relationship of moisture ratio from the experimental and statistically simulated data versus drying time at various conditions. Table III listed the statistical analysis values of □2, MBE, and RMSE of various drying conditions. It is apparent that Page's model provided a good representation of the experimental results with high correlation coefficient, low RMSE and χ^2 for all drying conditions.

The drying constant (k) in Page's model represents drying behavior [6]. The higher k-value showed an increased drying rate. The results of the drying coefficient k from Page's model were in agreement with prior sections that higher microwave power resulted in increased drying rate. The ranges of the drying coefficient k values from the experiment conducted at 400 and 800 W were 0.136-0.597 min-1 and 0.303-0.827 min-1, respectively. To compare the effect of power-off time at the same microwave power and vacuum pressure, the k values appeared in the descending order as follows: pulsed mode of 60s-on/60s-off, the continuous mode, and pulsed mode of 60s-on/120s-off.

To support the results from the investigation of the effect of vacuum pressure on the drying rate, as expected, the k values was directly proportional to vacuum pressure.

TABLE II
THE EFFECTIVE DIFFUSIVITY (D_{EFF}) AT VARIOUS DRYING CONDITIONS

Drying conditions			
Power	Vacuum Pressure	Heating Mode	$D_{eff}\times10^{8}$ (m^2/s)
400 W	20 cmHg	Continuous	0.506 ± 0.008
	30 cmHg	Continuous	0.787 ± 0.027
	40 cmHg	Continuous	0.884 ± 0.042
		60s-on/60s-off	0.911 ± 0.014
		60s-on/120s-off	0.520 ± 0.016
800 W	20 cmHg	Continuous	0.737 ± 0.016
	30 cmHg	Continuous	0.997 ± 0.013
	40 cmHg	Continuous	1.442 ± 0.063
		60s-on/60s-off	2.070 ± 0.058
		60s-on/120s-off	0.741 ± 0.024

Also from Page's model, n represented an order of the relationship between moisture ratio and drying time. The values of n for 800 W and 400 W were in the range of 0.477-0.633 and 0.560-0.796, respectively. The results imply that the relationship of moisture ratio and drying time was not likely a first order, which was in agreement with the drying of mint by Therdthai and Zhou [5].

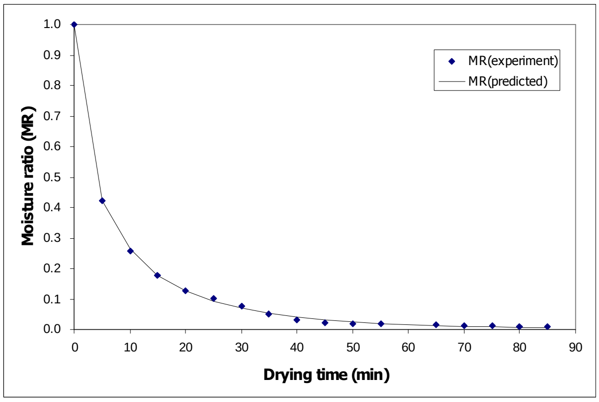

Fig. 4 The relationship of moisture ratio from the experimental and statistically simulated data versus drying time at 400 W, 40 cmHg, continuous heating

TABLE III
THE STATISTICAL ANALYSIS VALUES OF PAGE'S MODEL AT VARIOUS DRYING CONDITIONS

Power (W)	Vacuum Pressure (cmHg)	Heating Mode	k (min^{-1})	n	χ^2 $\times10^4$	MBE $\times10^3$	RMSE $\times10^{-2}$
400	20	Cont.	0.136	0.79	5.02	-9.28	2.15
	30	Cont.	0.166	0.77	1.23	-3.05	1.05
	40	Cont.	0.315	0.62	2.71	-2.30	0.48
		60s-on /60s-off	0.597	0.56	1.21	6.64	1.02
		60s-on	0.296	0.57	3.46	-1.66	0.05

		/120s-off					
800	20	Cont.	0.329	0.56	1.67	3.68	0.38
	30	Cont.	0.375	0.63	2.83	-1.39	0.49
	40	Cont.	0.597	0.56	6.84	-4.98	0.23
		60s-on /60s-off	0.821	0.47	1.60	4.65	0.35
		60s-on /120s-off	0.303	0.62	1.33	-2.08	0.23

IV. CONCLUSION

Fresh papaya cubes were dried using the microwave vacuum dryer. The effects of microwave output power, vacuum pressure, and power-off time on drying characteristics were determined. The drying rate of papaya cubes was directly proportional to microwave power and vacuum pressure. Pulsed mode drying showed a beneficial effect on drying rate compared to the continuous mode. However, too-long power-off showed adverse effect on the drying rate. The effective diffusivity was in agreement with parameter affecting the drying of papaya cubes. Based on Page’s model, the statistical analysis of the relationship between moisture ratio and drying time was satisfied. Parameters obtained from Page’s model showed a good agreement with experimental results.

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