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HEAT AND MASS TRANSFER IN DRYING OF CARROT BY RADIO FREQUENCY ASSISTED HEAT PUMP DRYING

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ABSTRACT

This study focused on the heat and mass transfer in radio (RF) assisted heat pump (HP) drying of carrots. The experimental drying of carrot by RF assisted HP drying method was conducted to evaluate the effect of RF power on drying efficiency including drying rate and heating rate. The input drying parameters were drying air temperature of 45°C, drying air velocity of 2.5 m/s and RF power of 0, 0.5 and 1.5 kW, in which, RF power of 0 was corresponding to HP drying method. The experimental drying results showed that in RF assisted HP drying method, the drying rate and heating rate were improved as compared to HP drying. The drying time was 480, 375 and 335 minutes corresponding to RF power of 0, 0.5 and 1.5 kW. The temperature of drying material reached the drying air temperature in about 25 and 30 minutes corresponding to RF power of 1.5 and 0.5 kW. While in HP drying, the temperature of drying material reached nearly the drying air temperature value in about 310 minutes. Besides, the comparison between the heat and mass equations solving results and experimental drying data was also carried out with the analysis results confirmed that the predicted data by numerically solving the heat and mass transfer equations could be used to predict the experimental data accurately.

Keywords: *Drying rate, heating rate, drying air temperature, drying air velocity, RF power.*

1. INTRODUCTION

Drying is a popular method and widely applied in foods and agricultural product processing. Agricultural products and foods could be preserved longer after being dried. The drying method and drying parameters such as drying temperature, drying air humidity and drying air velocity have a great influence on not only the structure, quality and shelf life of dried products but also the drying rate and energy consumption (Singh *et al.,* 2008; Pardeshi *et al.,* 2009; Waheed *et al.,* 2019; Abhishek *et al.,* 2020). Therefore, the selection of a suitable drying method is very important not only to improve the drying efficiency but also to maintain the sensory and nutritional quality of the dried products (Abhishek *et al.,* 2018; Villalobos *et al.,* 2018; Kadriye *et al.,* 2019; Bei *et al.,* 2020; Katarzyna *et al.,* 2021).

Currently, in the world, many different drying methods have been applied for agricultural products and foods such as hot air convection drying, heat pump drying, vacuum drying, infrared drying, microwave drying and RF drying. Drying technique using RF has been studied and developed because of a number of outstanding advantages such as: volumetric heating mechanism increases heating rate; the temperature gradient and the moisture gradient are in the same direction, that supports the diffusion of moisture in the drying material to increase the drying rate (Yang *et al.,* 2018; Zhou *et al.,* 2019; Zhang *et al.,* 2019; Ran *et al.,* 2019; Peng *et al.,* 2019; Wang *et al.,* 2020; Wang *et al.,* 2021; Shewale *et al.,* 2021). Wang *et al.,* (2013) studied the experimental drying of macadamia nuts by RF and the results showed that the RF power significantly increased the drying rate and improved the uniformity of the temperature and moisture distribution within the dried products. Wang *et al.,* (2014) have compared the drying efficiency of two methods of drying macadamia nuts as: RF assisted hot air-drying method and hot air-drying method. The experimental results showed that in RF assisted hot air-drying method, the drying time was reduced by 50% and the product quality was significantly improved. Jiao *et al.,* (2016) studied the experimental drying of peanuts by RF assisted hot air-drying method. The results showed that the drying efficiency, the life, and quality of the dried products were improved. Xu Zhou and Shaojin Wang (2019) studied the drying techniques using RF for drying agricultural products and foods, in which, the RF volumetric heating mechanism significantly improved the drying rate and the quality of the dried products. Le Anh Duc *et al.,* (2022) conducted the RF assisted heat pump drying of Ganoderma lucidum and the experimental drying results showed that increasing RF power increased the moisture ratio and reduced the drying time significantly.

The heat and mass transfer in the drying process using RF for food and agricultural products were studied (Zhi *et al.,* 2016a, 2016b; Ferruh *et al.,* 2017; Hankun *et al.,* 2017; Nguyen *et al.,* 2022). In the studies, the heat and mass transfer equations were established, in which, the convective heat exchange, the heat conduction, and the heat generated within the material by RF power dissipation were considered.

Carrot is an agricultural product with high nutritional value that can help people to improve their health. Carrot is one of the most common and popular vegetables today. Carrot contains a high content of α and β carotene, biotin, potassium, vitamin A (from β carotene), vitamin K1 (phylloquinone) and vitamin B6 (Van *et al.,* 1996; Sumnu *et al.,* 2005; Zielinska *et al.,* 2010). Carrot can improve the immune system, promote

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eye health, decrease high blood pressure and promote digestion. Carrot has a variety of colors such as orange-yellow, red, yellow, and purple (Prasad *et al.,* 2016). Like other vegetables, carrot has a high moisture content (about 92%, w.b) so they are rotted and spoilt easily after harvest (Haq R. and Prasad K., 2015). There have been many studies on the methods of drying carrots to improve drying efficiency and quality of dried products. Mustafa *et al.,* (2017) conducted the experimental drying of carrots by heat pump drying method and infrared combining heat pump drying method. The experimental results showed that the combining drying method increased the drying rate and reduced the drying time by 48%. Raees-ul Haq *et al.,* (2018) carried out the experimental drying of carrots using hot air convection drying method combining with microwave heat pre-treatment. The results showed that the heat pre-treatment using microwave increased the drying rate and reduced the drying time significantly, and the carrot samples kept the color and flavor better after drying. Yiting *et al.,* (2020) conducted the experimental drying of carrots by two drying methods: infrared drying and ultrasound assisted infrared drying method. The results showed that in ultrasound assisted infrared drying, drying durations shortened by 21% and the dried products achieved higher quality compared to only infrared drying method.

There were hardly any previous studies on the heat and mass transfer in carrot drying process using RF technique. The study of heat and mass transfer in drying of carrot by RF assisted HP drying is essential in order to clarify the heat and mass transfer mechanism in drying process. Which would become the foundation of improving the effective drying method, which could improve not only the drying rate but also the quality of dried products. The objective of the study focused on: i) to conduct the experimental drying of carrot by RF assisted HP drying method to evaluate the effect of RF power on drying efficiency; ii) to conduct the comparison between the heat and mass equations solving results and experimental drying data.

2. MATERIALS AND METHODS

2.1 Material

Carrots used in the study were fresh orange-yellow carrots with length of 18 – 22 cm, diameter of 2.5 – 3 cm. Carrot samples were cut off the roots, washed and sliced into pieces with 10 mm thickness. Carrots had an initial moisture content of 92 ± 0.1% wet basis (%, w.b). The weight of carrots used for each drying batch was 3 kg.

2.2 Experimental Method

The experimental drying was carried out under controlled temperature and RF power. The RF assisted HP dryer used for drying experiment was given in Fig. 1. The dryer included a RF generator operating with the frequency of 27 MHz and the maximum capacity of 5 kW and a heat pump operating with the maximum capacity of 0.85 kW (Nguyen Hay *et al.,* 2018). The carrot samples were placed on a plastic mesh grid drying tray which was placed between two RF electrodes in a drying chamber. The RF electrodes were separated with distance of 150 mm by Teflon plastic bars.

In which, the drying air was sucked by an air pump and passed through the heat pump unit. After passing through the heat pump, the drying air would have the specific temperature, humidity and velocity. The drying air continued to enter the drying chamber, where the drying air combined with RF to perform the carrot drying process. The experimental drying of carrot was conducted with controlled drying parameters as drying air velocity of 2.5 m/s, drying air temperature of 45°C, and RF power of 0, 0.5 and 1.5 kW, in which, the RF power of 0 kW was corresponding to HP drying method.

The initial moisture content of the drying air was determined by a moisture analyzer (DBS 60-3 model, maximum analyzed sample weight: 60 g ± 0.01%, analyzed moisture range: 0 - 100%).

An electronic scale (GS-6202) with standard measurement value of 6000 ± 0.01 g was used to weigh the material samples during the drying process. The weight measurement was performed regularly every 30 minutes. Each experiment was conducted until the drying material achieved the moisture content of 11 ± 0.1 (%, w.b) and completed in triplicates.

The temperature of carrot sample was measured by a temperature sensor (MF59 100K) with measurement ranges of -40°C – 300°C ± 0.01°C. The temperature sensor could record the temperature value versus drying time via an integrated circuit that was connected to computer software. The small head of sensor was fixed inside the carrot sample. The carrot sample's temperature during the drying process was recorded by computer software every 20 minutes.

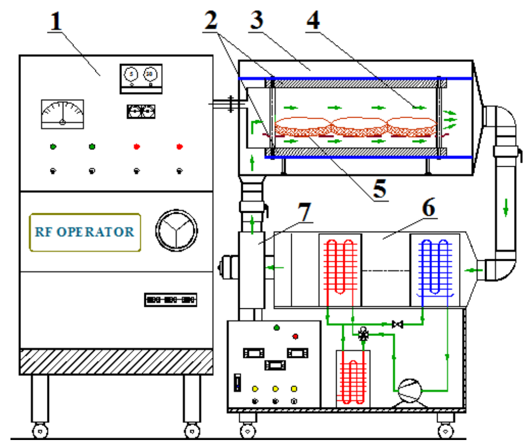

Fig. 1 The RF assisted HP dryer model

In which, 1. RF generator; 2. RF electrodes; 3. drying chamber; 4. drying air direction; 5. drying tray; 6. heat pump; 7. air pump

2.3 Method of comparing between the heat and mass equations solving results and experimental drying data

The heat and mass transfer equations were used in the study as below (Nguyen Hay *et al,* 2022):

The heat transfer equation:

$$\underbrace{\rho C_p \frac{\partial t}{\partial \tau}}_{q_{internal}} = \underbrace{\lambda \frac{\partial^2 t}{\partial x^2}}_{q_{conduction}} + \underbrace{r\rho_k \frac{\partial w}{\partial \tau}}_{q_{vaporization}} + q_{RF} \quad (1)$$

The mass transfer equation:

$$\frac{\partial w}{\partial \tau} = D\frac{\partial^2 w}{\partial x^2} \quad (2)$$

In the heat transfer equation, $q_{internal}$ is internal energy change within the material, and $q_{conduction}$ is heat transfer by conduction within the material, $q_{vaporization}$ is the heat required for vaporization of moisture within the material, and q_{RF} is heat generated within the material by RF power dissipation.

The initial conditions are given as:

At $\tau = 0$:

$$t(x,0) = t_0; w(x,0) = w_0 \quad (3)$$

The heat and mass transfer boundary conditions ($\tau > 0$) are given as:

At x = 0:

$$\left.\frac{\partial t}{\partial x}\right|_{x=0} = 0; \left.\frac{\partial w}{\partial x}\right|_{x=0} = 0 \quad (4)$$

At x = δ/2:

$$-\lambda\left.\frac{\partial t}{\partial x}\right|_{x\equiv x_s} = \alpha(t_a - t)\Big|_{x\equiv x_s} - r\rho_k\beta_M(w - w_e)|_{x\equiv x_s} \quad (5)$$

$$-D\left.\frac{\partial w}{\partial x}\right|_{x\equiv x_s} = \beta_M(w - w_e)|_{x\equiv x_s} \quad (6)$$

The finite difference method was used to solve numerically the heat and mass transfer equations (Nguyen Hay *et al.,* 2022). In which, the Matlab 2021 software was applied for programming the heat and mass transfer algorithm to solve the heat and mass transfer problem.

Thermo-physical properties of carrot and the drying conditions used to conduct the simulation and experimental drying were given in Table 1.

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In which, the correlation formula between the value of M (d.b) and w (w.b) was given as below:

$$M = \left(\frac{1}{w} - 1\right)^{-1} \quad (7)$$

The correlation formula between the value of T (K) and t (ºC) was given as below:

$$T = t + 273 \quad (8)$$

Table 1 Drying condition and carrot property.

Parameters	*Value*	*References*
The thickness of samples, 2δ (m)	0.01	
λ (W/m.ºC)	$\frac{0.148 + 0.641M}{1 + M}$	(Sweat, 1974)
ρ (kg/m³)	$\frac{1490(1 + M)}{1 + 1.45M}$	(Zogzas *et al.,* 1994)
C_p, (kJ/kg.ºC)	1.755 + 2.345M	(Ratti and Crapiste, 1995)
r (kJ/kg)	$2501.3 - 2.301T_a - 0.00142T_a^2$	(Thorpe, 2003)
w_e (d.b)	0.049	(Ahmet *et al.,* 2016)
w_i (w.b)	0.92	
t_i (ºC)	27	
t_a (ºC)	45	
R_H	18%	
α (W/m².ºC)	12.323	
$β_M$ (m/s)	0.012	

The parameters as Root mean square error (RMSE) and Mean absolute error (MAE) were used to conduct the comparison between the heat and mass equations solving results (predicted data) and experimental drying data. The low value of RMSE and MAE were considered as a criteria for goodness of fit and defined in Eq. (9) and Eq. (10) (Duc *et al.,* 2009):

$$RMSE = \left[\frac{1}{N}\sum_{I=1}^{N}\left(X_{Exp} - X_{Pre}\right)\right]^{0.5} \quad (9)$$

$$MAE = \frac{1}{N}\sum_{I=1}^{N}\left(\frac{|X_{Exp} - X_{Pre}|}{X_{Pre}}\right) \quad (10)$$

3. RESULTS AND DISCUSSIONS

3.1 The Effect of RF Power on Drying Rate

The change of the moisture content of the drying material during RF assisted HP drying of carrot was presented graphically in Fig. 2. As shown in Fig. 2, the carrot's moisture content reduction trend during drying process corresponding to different drying modes including both predicted data and experimental data was relatively similar. The RF-assisted HP drying method significantly improved the drying rate and shortened the drying time as compared to HP drying and when RF power increased, the drying rate increased. The drying time required for the carrot's moisture content to reach 11 (%, w.b) was 480, 375 and 335 minutes corresponding to RF power of 0, 0.5 and 1.5 kW, in which, RF power of 0 was corresponding to HP drying method. At RF power of 1.5 kW, the drying time decreased 11% and 30% as compared with drying time at RF power of 0.5 kW and 0 kW. This was explained by the fact that when RF power increased, the drying material would absorb more RF energy which augmented the heating rate. Thus, the process of moisture diffusion in the material would take place faster and increase the drying rate. This heating mechanism was similar to the previous studies of RF heating mechanism for agricultural products (Darvishi *et al.,* 2013; Ahmet *et al.,* 2015; Wang *et al.,* 2020; Wang *et al.,* 2021; Shewale *et al.,* 2021; Nguyen *et al.,* 2022). This is the advantage of the RF heating mechanism, and the combination of RF and HP could obtain an effective drying method, in which, the RF power associated with the low humidity drying air in supporting the drying process to improve the drying rate.

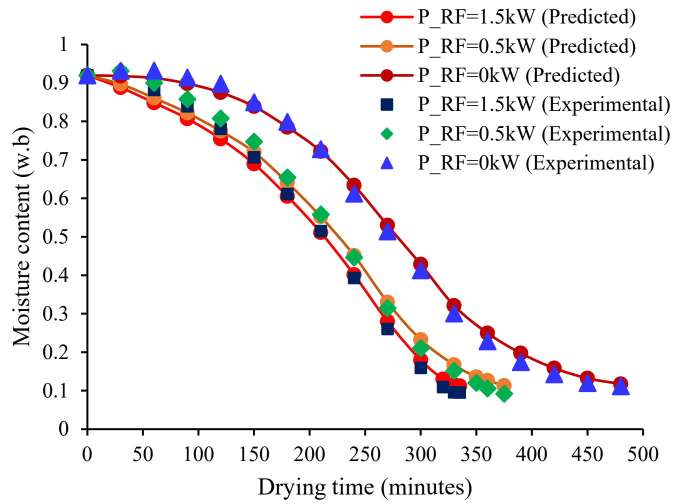

Fig. 2 The relationship between the moisture content of the drying material versus the drying time.

3.2. Effect of RF Power on the Temperature of Drying Material

The change of average temperature of drying material during RF assisted HP drying process was shown graphically in Fig. 3.

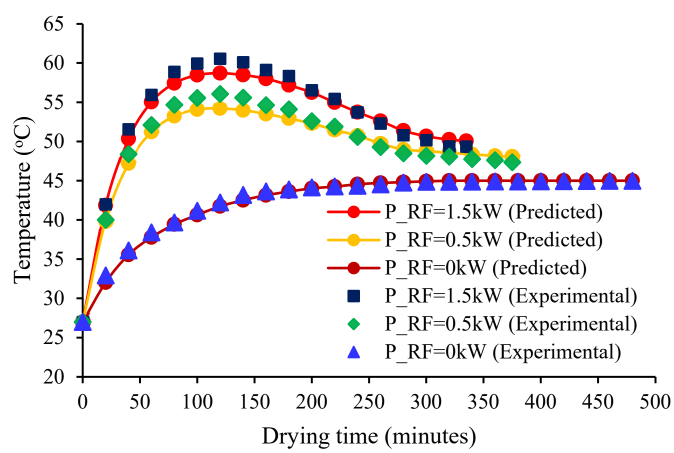

Fig. 3 The relationship between the temperature of the drying material versus the drying time.

As shown in Fig. 3, in RF-assisted HP drying, the heating rate was significantly higher than HP-only drying and the increase of RF power would induce the heating rate. This was explained by the RF heating mechanism, when the material absorbed more RF power, the heat generation inside the material by the wet dipole molecules oscillation became faster and induced the heating rate (Lixia *et al.,* 2016; Samet *et al.,* 2017; Wang *et al.,* 2020; Wang *et al.,* 2021; Shewale *et al.,* 2021; Nguyen *et al.,* 2022). The temperature of drying material reached the drying air temperature in about 25 and 30 minutes corresponding to RF power of 1.5 and 0.5 kW. While in HP drying, the temperature of drying material reached the nearly drying air temperature value in about 310 minutes. In RF-assisted HP drying process, after the material's temperature reached the drying air temperature value, it continued to increase beyond the drying air temperature because the moisture within the drying material still absorbed RF power, that caused the material's temperature to continue increasing. This result was agreed with the previous studies of RF heating mechanism (Wang *et al.,* 2013; Zhi *et al.,* 2016; Nguyen *et al.,* 2022). After reaching the highest value, the material's temperature decreased gradually to the value of drying air temperature. This stage lasted till the end of the drying process. This was indicated by RF heating mechanism, the moisture content of drying material reduction would decrease RF energy absorption within the material, that caused the decrease of the material's temperature. This was agreed with the RF heating mechanism in previous study (Samet Ozturk *et al.,* 2016; Nguyen *et al.,* 2022).

3.3. Comparison Between Predict Data and Experimental Data

The predicted data and the experimental data of material's moisture and temperature were presented graphically in Fig. 2 and Fig. 3. Fig. 2 and Fig. 3 indicated that the moisture reduction, and the change of the average material's temperature during drying process corresponding to both predicted data and the experimental data had the similar tendency and profile.

Two-sample comparison analyzation by Statgraphics Centurion XVII on computer was used to identify the value of P-Ratio, which is the value of relational comparing parameter between predicted data and experimental data. Besides, the value of RMSE and MAE were calculated by Eq. (9) and Eq. (10) to validate the predicted data. The results of comparison parameters were given in Table 2.

Table 2 The analyzing parameters of comparing the predicted data and experimental data

RF power (kW)	*The moisture content parameter*			*The temperature parameter*		
	P-value	*RMSE*	*MAE*	*P-value*	*RMSE*	*MAE*
0	0.805	0.122	4.28%	0.915	0.492	0.61%
0.5	0.792	0.142	6.32%	0.889	0.886	1.52%
1.5	0.802	0.136	6.27%	0.905	0.899	1.55%

The result in Table 2 showed that the P-value was greater than 0.05, there was not a statistically significant difference between the means of the two variables at the 95% confidence level. Besides, the value of RMSE and MAE were low. Thus, the analysis results confirmed that the predicted data by numerically solving the heat and mass transfer equations could be used to predict the experimental data accurately.

4. CONCLUSION

The experimental drying of carrot by RF assisted HP drying method was conducted to evaluate the effect of RF power on drying rate and heating rate. When RF power increased, the drying rate and heating rate increased significantly. At RF power of 1.5 kW, the drying time reduced by 11% and 30% as compared with drying time at RF power of 0.5 kW and 0 kW. The time period for heating the material to reach the drying air temperature was 25, 35 and 310 minutes corresponding to RF power of 1.5, 0.5 and 0 kW. Besides, the analyzing parameters of comparing the predicted data and experimental data was determined and the analysis results confirmed that the predicted data by numerically solving the heat and mass transfer equations could be used to predict the experimental data accurately.

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NOMENCLATURE

C_p	specific heat capacity	kJ/kg.°C
w_e	equilibrium moisture content	w.b
w_i	initial moisture content	d.b
t	temperature	°C
T	absolute temperature	K
R_H	drying air humidity	%
M	moisture content	d.b
r	latent heat of vaporization of moisture	kJ/kg

Greek letters

δ	thickness	m
λ	thermal conductivity	W/m.°C
ρ	density	kg/m^3
α	convective heat transfer coefficient	W/m^2.°C
β_M	convective mass transfer coefficient	m/s
X_{Exp}	experimental value of moisture content or temperature	
X_{Pre}	predicted value of moisture content or temperature	

Subscripts

a	drying air
e	equilibrium
i	initial

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