



NUMERICAL ASSESSMENT OF A MICROWAVE-HEAT PUMP DRYING OF SLICED TURMERIC

Duc Nam Nguyen, Thi Viet Linh Nguyen, Xuan Binh Nguyen and Ngoc Quy Nguyen

School of Electrical and Electronic Engineering

Hanoi University of Industry

No. 298 Cau Dien Street, Tay Tuu Ward

Hanoi, Vietnam

e-mail: nguyenducnam@hau.edu.vn

Abstract

Microwave-heat pump drying is a low-temperature drying technique that maintains product quality with an accelerated drying rate under the microwave-thermal effect. In this work, a mathematical model of the sliced turmeric drying process is developed for both pure and microwave-assisted heat pump drying processes. The conjugate heat and mass conservation equations are written based on the concept of effective thermal conductivity and effective moisture diffusivity. Based on experimental data, the moisture diffusivity is determined based on the inverse method by minimizing the discrepancy between

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the numerical and experimental observations. The results indicate that a microwave power intensity of 1.5 W/gram can help to enhance the effective moisture diffusivity by more than 30%. Additionally, the impact of microwave heating on the moisture content and temperature profile with different slice thicknesses is investigated numerically. In the future, the drying kinetics predicted by the proposed model can be readily used as essential input for designing and operating the microwave-assisted heat pump drying system.

1. Introduction

In recent years, heat pump drying has emerged as a potential drying technology due to its ability to maintain low temperatures, save energy and limit product quality degradation compared to traditional hot convection drying methods [1]. However, the disadvantage of this method is that the drying speed is still slow, leading to long processing times. To overcome this problem, many studies have proposed incorporating microwave energy sources into the drying process. Microwave heating has the advantage of creating a volumetric heating effect, shortening the drying time and promoting moisture migration due to the internal pressure gradient in the material [2]. Previous works have shown that the combination of microwave drying - heat pump significantly reduces drying time, while preserving the color, flavor and bioactive ingredients of the product [3]. Several studies have investigated the influence of microwave power on drying kinetics and have shown that appropriate microwave power can significantly improve the effective moisture diffusion coefficient [4]. Others have focused on modeling, in which heat and moisture transfer equations are built based on the assumptions of homogeneous or semi-homogeneous materials [5]. However, many models are still simple, not fully reflecting the complex interactions between temperature, humidity and microwave power.

For turmeric - a valuable medicinal herb containing curcumin - the drying process plays a key role in preserving its quality. Some works have conducted experimental studies on turmeric drying under different temperature, thicknesses and air speed conditions [6-8], but mathematical

models simulating microwave-heat pump drying of sliced turmeric are very limited. In particular, the effect of microwaves on the effective moisture diffusion coefficient, as well as the change in moisture and heat distribution in turmeric slices of different thicknesses, has not been clarified. This gap requires studies that combine both experimental and mathematical modeling to predict and analyze the drying kinetics in detail.

Based on the above practices, this study focuses on the following main contents: (i) building a mathematical model to simultaneously describe the heat and moisture transfer processes in turmeric slices under pure heat pump drying conditions and combined microwave-heat pump drying conditions; (ii) How does microwave power affect the effective moisture diffusion coefficient and the change in moisture content during the drying process? (iii) What role does the thickness of turmeric slices play in the heat-moisture distribution when microwave is assisted? (iv) How can the model results be applied in the design and operation of microwave-heat pump drying systems on an industrial scale?

To address these issues, the study develops a mathematical model based on the equations of conservation of energy and mass, in which the effective parameters are determined by regression methods based on experimental data. The simulation results allow analyzing the effects of microwave power as well as slice thickness on drying kinetics. Thereby, the study contributes more scientific basis for optimizing the turmeric drying system, while opening directions for application to other agricultural products and medicinal herbs.

2. Model Development

2.1. Heat and mass transfer equations

The process of moisture transfer in plant foods during drying is extremely complex. Moisture transfer in the sample involves many transport mechanisms, including liquid capillary flow, liquid diffusion, water vapor diffusion and air diffusion under the influence of significant volume

shrinkage of the sample and under the influence of internal heat sources in the sample [9]. Moisture diffusion on the sample surface is controlled by air temperature, relative humidity and velocity. The change in moisture content over time is difficult to predict experimentally. To predict the change in moisture content over time, a predictive mathematical model of the drying process is established, which can also be used to optimize the design and operation of the drying equipment reasonably. In this study, the drying sample is sliced turmeric which is assumed to be isotropic and homogeneous. A thin layer of turmeric slices with a thickness less than five times the diameter is introduced into the drying equipment, the drying agent is air contacting both sides of the turmeric slices. Therefore, the problem of heat and mass transfer is a one-dimensional problem. The air velocity, temperature and relative humidity are maintained constantly throughout the drying process.

Mass balances

The two-phase liquid-vapor mixture inside the sample is simplified into a single-phase substance called “moisture”. In this way, moisture migration is assumed to be due only to the influence of the moisture gradient. Thus, the moisture conservation equation is written as

$$\frac{\partial X}{\partial t} = \nabla \cdot (D_{eff} \nabla X). \quad (1)$$

In equation (1), $X = \frac{M_w}{M_s}$ (kg water/kg dry solid) is the dry based moisture content, where M_w and M_s (kg) denote the mass of moisture and dry solid, respectively. D_{eff} (m²/s) presents the effective moisture diffusivity where the moisture transport mechanisms are lumped.

Energy balance

The energy conservation equation is written based on ideal where the change of energy density is due to the conductive heat flux and the convective enthalpy flux resulting from the moisture flow. Thus, the heat

transfer equation can be expressed as

$$\frac{\partial}{\partial t}(\rho_o c_s T + \rho_o X c_l T) + \nabla \cdot [c_l (-D_{eff} \rho_o \nabla X) T] - \nabla \cdot [\lambda_{eff} \nabla(T)] - \dot{q}_{MW} = 0, \quad (2)$$

where λ_{eff} (W/m.K) is the effective thermal conductivity, c_s and c_l (J/kg.K) are the specific heat capacity of solid and liquid water, respectively. The density of dry solid is denoted as ρ_o (kg dry solid/m³), \dot{q}_{MW} is the internal heat source, considered as a value depending on the microwave power density on the surface and the distance from the surface to the element according to Lambert's law.

Thus, the heat and mass transfer conservation equations (1) and (2) are built to describe the drying process using a combined microwave heat pump. If only the heat pump is used for drying, then $\dot{q}_{MW} = 0$. When microwave heating is applied, the microwave heat source \dot{q}_{MW} is calculated using equation (3):

$$\dot{q}_{MW} = Q_0 \exp[-2\gamma(L - x)]. \quad (3)$$

Initial and boundary conditions

The sample with uniform initial moisture content X_o and defined initial temperature T_o is subjected to the convective drying process. The boundary heat and mass transfer equations are expressed as

$$-\rho_o \nabla(X) = \beta \rho_g (Y_{surf} - Y_g), \quad (4)$$

$$-\lambda \nabla T = \alpha (T_{surf} - T_g) - \Delta h_{evp} \beta \rho_g (Y_{surf} - Y_g), \quad (5)$$

where ρ_g is the dry air density (kg dry air/m³), Y_{surf} and Y_g are the moisture contents of air at the sample surface and in the bulk air (kg vapor/kg dry air). T_{surf} and T_g present the surface and bulk air temperatures, respectively. Δh_{evp} presents the evaporation enthalpy of

liquid water, α and β are the convective heat and mass transfer coefficients which are determined by using the modified Ranz-Marshall correlations [10]:

$$Nu = 2 + 0.6 Re^{\frac{1}{2}} Pr^{\frac{1}{3}}, \quad (6)$$

$$Sh = 2 + 0.6 Re^{\frac{1}{2}} Sc^{\frac{1}{3}}. \quad (7)$$

The thermal properties, including specific heat capacity and density, are computed from the mass fractions of constitution components. Effective thermal conductivity is calculated by the Levy and Krischer formula:

$$c = \sum_1^n x_i c_i \quad \text{and} \quad \rho = \left(\sum_1^n \frac{x_i}{\rho_i} \right)^{-1}, \quad (8)$$

$$\lambda = \frac{\lambda_2 [(2 + \Lambda) + 2(\Lambda - 1)F_1]}{(2 + \Lambda) - (\Lambda - 1)F_1}. \quad (9)$$

The constituent analysis was done in the School of Biotechnology and Food Technology, Hanoi University of Science and Technology. The results are presented in Table 1.

Table 1. Mass fraction of constitution components of fresh turmeric

Constituent	Moisture	Protein	Fat	Carbohydrate	Fiber	Ash
Mass fraction (%)	84.15	1.19	1.01	10.15	1.16	1.02

The developed heat and mass conservation equations and the boundary conditions are solved numerically by using volume element method (FVM). This method ensures energy and mass balance within the domain. A homemade FVM discretization and solution code was developed in MATLAB 2025a. After performing the mesh independent checking, a mesh with 50 nodes and time step of 1 sec is used in the rest of this work.

2.2. Experimental setup

To verify the proposed model, a heat pump drying system was fabricated at the Thermal Process Laboratory, Faculty of Electrical Engineering, Hanoi University of Industry. The schematic diagram of the system is shown in Figure 1. The device uses R134a refrigerant; humid air from the drying chamber passes through the evaporator to be cooled and dehumidified, then through the condenser to be heated. When needed, an electric heater is used to further adjust the temperature. The wind speed is controlled by an inverter, maintaining an average of about 1.26 m/s. The drying process was performed with drying temperatures varying in range from 35°C to 45°C. The microwave power was set at 1.5 W/gram.

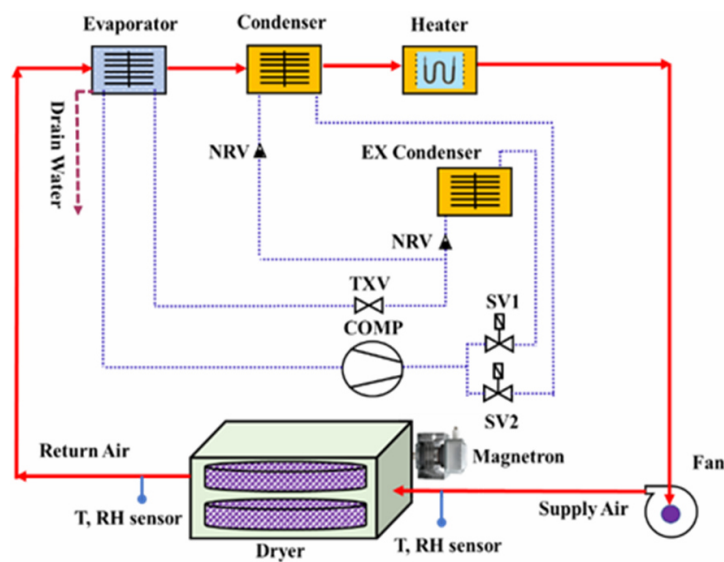


Figure 1. The systematical diagram of the microwave - heat pump dryer.

In the experiment, fresh turmeric was purchased from a local market, cleaned and sliced with a thickness of 1 mm, 2 mm and 3 mm. Each tray contained about 50 g of turmeric slices, evenly distributed in a thin layer on a perforated bamboo tray. The sample mass was weighed every 5 minutes, and the surface temperature was monitored with a Fluke 62 infrared thermometer. The initial and post-drying moisture contents were determined

using the standard drying method in a GMP 500 at 105°C for 2 hours. For each condition, the experiment was repeated three times to ensure the reliability of the results.

3. Results and Discussion

3.1. Model validation

Nine different experiments were performed for drying turmeric slices. The effective moisture diffusivity is determined for each drying experiment, and the established data are outlined in Table 2. As can be seen, for convection drying by heat pump, the effective moisture diffusion coefficient increases with drying temperature, increasing sample thickness. When microwave energy is added, the driving force of moisture diffusion inside the sample increases significantly, increasing the effective moisture diffusion coefficient. This trend is consistent with well-known theories, in which the effective moisture diffusion coefficient is assumed to be described by the Arrhenius equation. In addition, the effective moisture diffusion coefficient obtained from 3 mm thick samples is about 4 to 5 times higher than that of 1 mm thick samples for heat pump drying. When microwave action is applied, the effective moisture diffusion coefficient obtained from the samples increases about 2 to 3 times compared to the heat pump dried samples. This fact implies that the assumption of constant values of the moisture diffusion coefficient may not be suitable for the drying of turmeric slices. To further indicate the model's validity, the comparison between experimental and numerical moisture content, temperature and drying rate is shown in Figure 2 to Figure 4 for HP drying and Figure 5 to Figure 7 for HP-MW drying. As can be seen, experimental observations can be well reflected by the numerical results. The numerical results of moisture content fluctuate around the experimental data value with an error of less than 10%.

In addition to the moisture content and temperature evolution, the experimental constant and the decreasing drying rate cycle can be classified according to the diffusion model. This good agreement in the drying kinetics comparison shows that the model developed with the proposed parameters

can well reflect the nature of the drying process. This implies that the effective moisture diffusion coefficient determined above can be easily used for experimental drying conditions.

Table 2. The effective moisture diffusivity of turmeric slices

Drying temperature (°C)	Sample thickness (mm)	D_{eff} (m ² /s)	
		HP	HP-MW
35	1	2.152×10^{-11}	4.877×10^{-11}
40	1	2.321×10^{-11}	5.264×10^{-11}
45	1	2.703×10^{-11}	6.166×10^{-11}
35	2	6.045×10^{-11}	15.44×10^{-11}
40	2	6.712×10^{-11}	16.40×10^{-11}
45	2	7.153×10^{-11}	18.84×10^{-11}
35	3	8.829×10^{-11}	28.35×10^{-11}
40	3	10.29×10^{-11}	31.24×10^{-11}
45	3	11.24×10^{-11}	33.14×10^{-11}

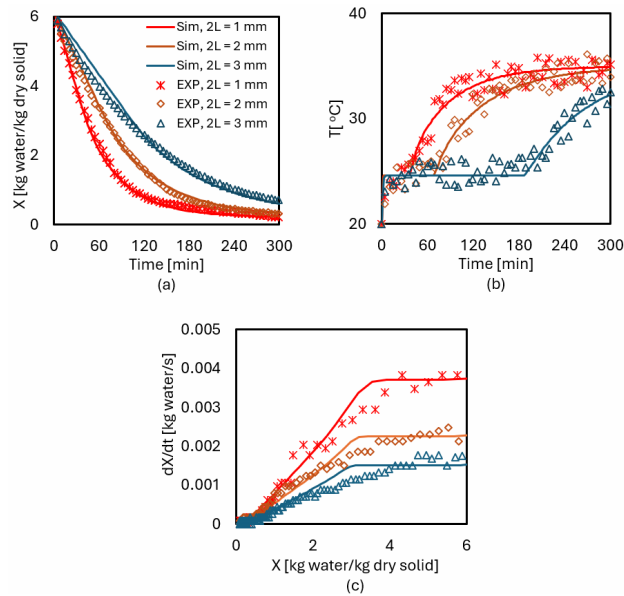


Figure 2. The HP experimental and numerical moisture content (a), temperature (b), and drying rate (c) obtained with the temperature at 35°C.

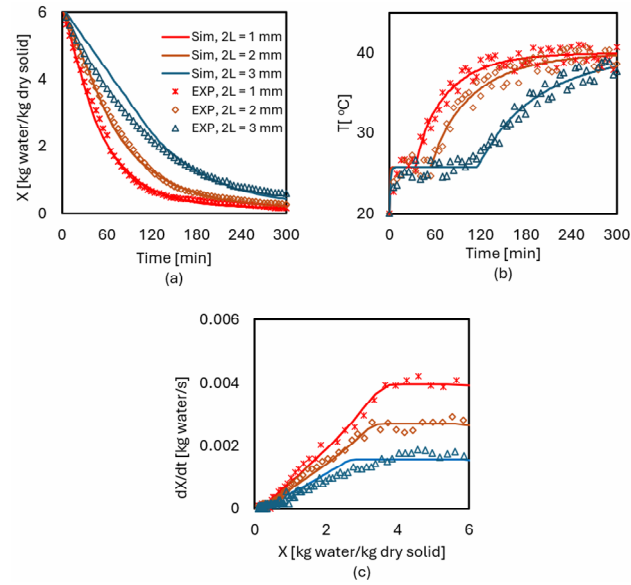


Figure 3. The HP experimental and numerical moisture content (a), temperature (b), and drying rate (c) obtained with the temperature at 40°C.

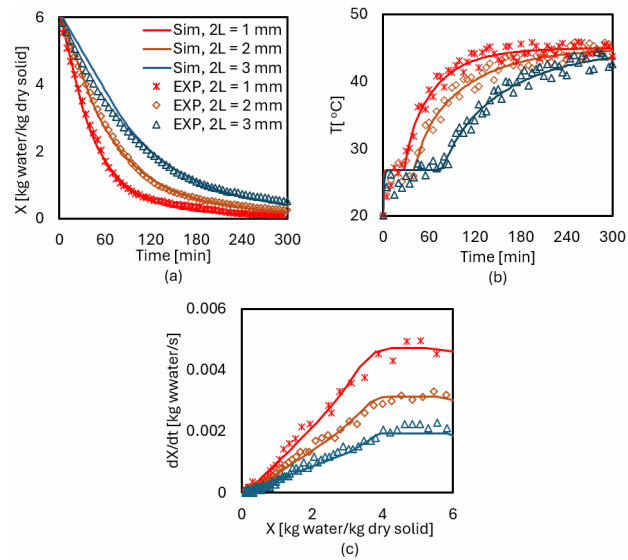


Figure 4. The HP experimental and numerical moisture content (a), temperature (b), and drying rate (c) obtained with the temperature at 45°C.

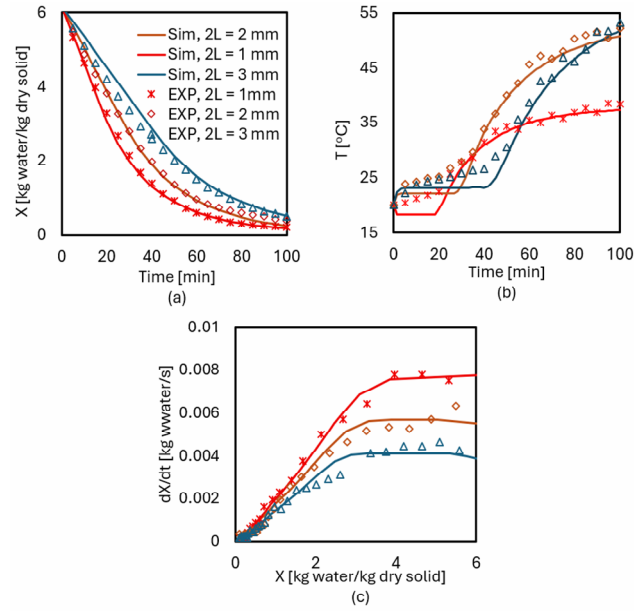


Figure 5. The MW-HP experimental and numerical moisture content (a), temperature (b), and drying rate (c) obtained with the temperature at 35°C.

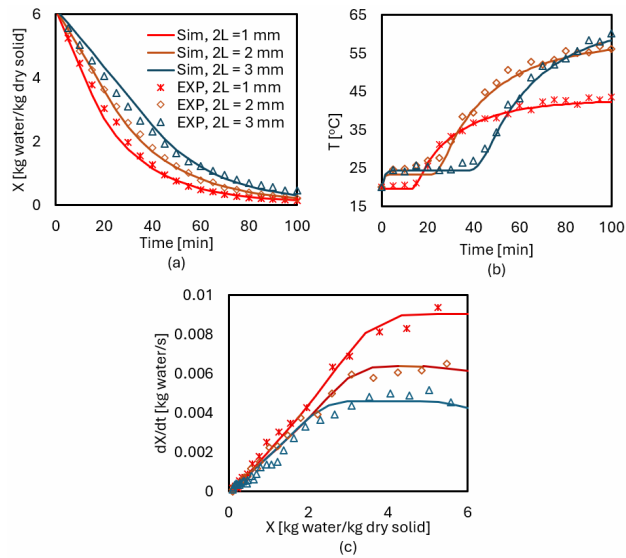


Figure 6. The MW-HP experimental and numerical moisture content (a), temperature (b), and drying rate (c) obtained with the temperature at 40°C.

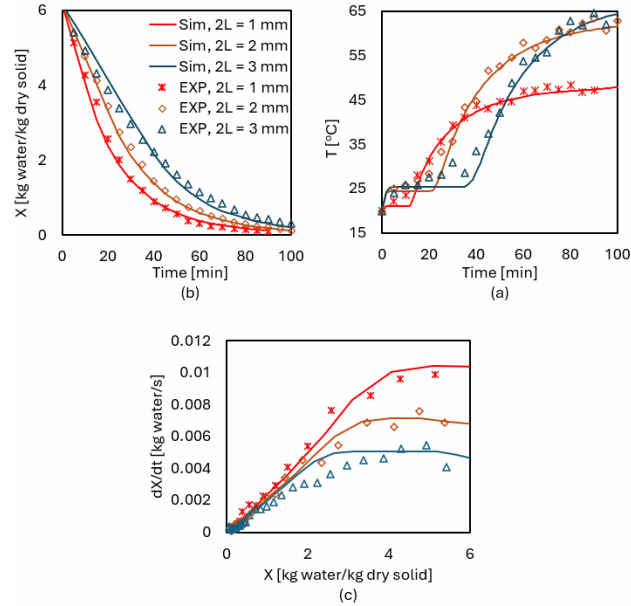


Figure 7. The MW-HP experimental and numerical moisture content (a), temperature (b), and drying rate (c) obtained with the temperature at 45°C.

3.2. Impact of microwave heating effect on drying kinetic

To further clarify the effect of microwaves on drying rate, the numerical results for temperature distribution and moisture content are presented in Figures 8 and 9. Temperature and moisture content distribution inside 3 mm thick slices during HP and HP-MW drying at 45°C for the first 100 min with a time step of 20 min. According to the simulation results presented in Figure 8 for the case of pure HP drying, the temperature tends to be uniform in space from the center ($x/L = 0$) to the surface ($x/L = 1.5$). This can be explained by the fact that due to the thin thickness of the slice, the small Biot standard value, the internal temperature distribution is uniform. With such a temperature distribution, the transport of moisture from the center to the surface is only carried out by the moisture gradient inside the slice. On the contrary, in the case of HP-MW drying, the temperature at the center tends to be higher than the surface temperature (Figure 9(a)). Inside the cross-section, a temperature gradient will form in the same direction as the

humidity gradient (Figure 9(b)). The formation of this temperature gradient will enhance the moisture transport process according to the Soret effect [11].

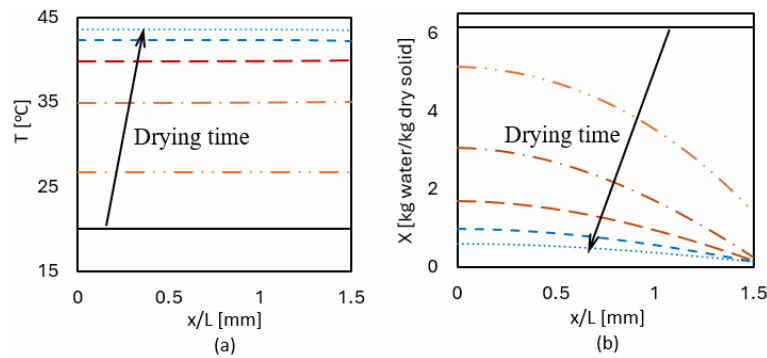


Figure 8. Temperature (a) and moisture content (b) distribution inside 3 mm thick slices during HP drying at 45°C.

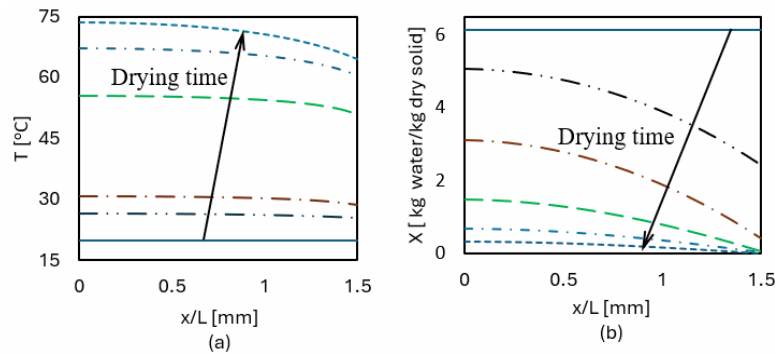


Figure 9. Temperature (a) and moisture content (b) distribution inside 3 mm thick slices during MW-HP drying at 45°C.

4. Conclusion

In this work, the conjugate heat and mass transfer during the microwave-assisted heat pump drying is modeled by using the concept of effective thermal conductivity and moisture diffusivity. Based on the experimental observations, the effective moisture diffusivity is determined by the inversed method. The results indicates that the obtained moisture diffusivity can be

used readily in a range of drying temperature for both pure heat pump drying and microwave-assisted heat pump drying processes. Additionally, by applying a microwave power intensity of 1.5 W/gram, the effective moisture diffusivity can be enhanced more than 30% compared to pure heat pump drying. In the future, the proposed model can readily pave the effective way designing and operating the microwave-assisted heat pump drying system by providing the trustworthy drying kinetics.

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