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Heat and mass transfer law during microwave vacuum drying of rice

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RESEARCH ARTICLE

Abstract

In order to obtain the microwave vacuum drying characteristics of rice and the change in law of temperature and humidity, the mechanism of water diffusion and migration in the drying process was analyzed based on the multiphase flow in porous media, the change model of moisture content was established, and the microwave heating process coupled with electromagnetic field and mass heat field was simulated. The accuracy of the multiphase porous medium model was verified by measuring the moisture changes during rice drying under different vacuum degrees. The results show that the temperature distribution of rice during heating is high in the center and low around, and the vacuum degree hardly affects the change in rice temperature. The capillary pressure in rice gradually increases, and the equilibrium vapor pressure gradually decreases during drying. The estimated moisture content reduced from 0.25 to 0.189, 0.177, and 0.169, and the experimental value decreased from 0.25 to 0.186, 0.177, and 0.167 after drying the rice for 60 min at vacuum of 0.02 MPa, 0.04 MPa, and 0.06 MPa, respectively. The experimental value was in agreement with the calculated value. The higher the vacuum degree, the faster the drying speed, and this finding provided a new idea for improving the drying efficiency.

Keywords: capillary pressure; equilibrium vapor pressure; microwave drying; moisture content; porous media; vacuum degree

Introduction

Rice has a long history of planting worldwide as an essential primary food. Rice is susceptible to mildew infection during storage, which deteriorates its quality. The secondary metabolites of mildew could cause severe risks to human and animal health (Chen *et al.*, 2021). Therefore, the drying treatment of rice is an indispensable step after harvest. Before entering the warehouse, a drying treatment must be carried out to make its moisture content reach the usual storage standard.

Microwave drying is widely used in the field of food drying due to the rapid drying speed caused by internal evaporation (Nisoa *et al.*, 2021; Zhou *et al.*, 2019). As a combined drying technology, microwave vacuum drying takes advantage of microwave heating and vacuum dehydration (Cao *et al.*, 2019). Additionally, it has the benefits of energy conservation, quick drying times, short processing times, considerable microwave energy penetration depth, rapid and precise electronic control, clean heating process, and the ability to lower the heat needed to evaporate water from food materials (Dash *et al.*, 2021). Xu *et al.* (2020) found that microwave vacuum drying is the most effective drying method for fresh okra compared to hot air drying and vacuum dehydration freeze drying. Carvalho *et al.* (2021) studied the microwave vacuum drying of barley malt and found that microwave vacuum technology is an attractive alternative for barley malt drying. Monteiro *et al.* (2018) suggested that microwave vacuum drying has great potential to produce dried and crispy fruits and vegetables. Zielinska *et al.* (2018) found that microwave–vacuum pretreatment accelerates mass transfer during the osmotic dehydration of cranberries.

When drying under standard atmospheric pressure, the water in the material is mainly discharged through boundary diffusion. When vacuum drying is adopted, the mass transfer resistance of water discharge under the action of internal and external pressure differences can be ignored (Tepe *et al.*, 2020). During the microwave drying process, the internal temperature of the material rises rapidly, and part of the internal liquid is converted into steam, forming a pressure difference. Driven by the pressure difference, the internal steam and moisture are transferred to the surface to achieve drying of the material. Dash *et al.* (2021) studied the effect of process parameters on the physicochemical properties and color of the fruit during drying. They used the response surface methodology to optimize the process parameters of microwave vacuum drying, and obtained high-quality dried fruit. Lei *et al.* (2020) studied the effects of microwave power, vacuum degree, and weight on grape moisture content during microwave vacuum drying. They believed that the Page model could accurately describe and predict grape moisture change during microwave vacuum drying. At present, a large number of literature have discussed the effect of process parameters on the drying process, but there are few studies on the laws of mass and heat transfer at the microscopic scale, especially the microwave vacuum drying process of rice based on multiphase flow in porous media. Microwave vacuum drying helps to reduce time and cost, but because rice microwave vacuum drying is a complex heat and mass transfer process, it may affect rice quality in the case of uneven heating (Cao *et al.*, 2017, 2019). The gradient of moisture content and temperature will cause thermal and mechanical stress inside the kernel, and this stress causes the seed to crack during the drying progress (Chayjan *et al.*, 2019). Only by correctly grasping the law of quality and heat transfer can we avoid these hazards in the drying process and obtain high-quality drying effects.

Microwave vacuum drying is a good method for drying because of its fast drying speed and energy saving. Moreover, a correct understanding of the characteristics of microwave vacuum drying of rice, as well as the laws of quality and heat transfer law of rice, will help us better grasp the direction of rice drying and provide a theoretical basis for the development of efficient rice drying machines in the future. This study explores the law of mass and heat transfer during the drying process and the change in the characteristics of related parameters during the rice drying process. To solve these problems, this study established the transfer equations of microwave vacuum drying of rice, developed a microwave vacuum drying finite element model, used experiments to verify the accuracy of the model, explored the influence of related parameters on the microwave vacuum drying rate of rice, and provided a theoretical basis for realizing efficient drying of rice.

Materials and Methods

Experiment and simulation

In this study, 100 g of rice was taken as a sample each time, the initial drying temperature was 20°C, the vacuum degree was 0.02 MPa, 0.04 MPa, and 0.06 MPa, and the microwave power was 400 W.

The moisture content of the rice was measured by the Grain Moisture Analyzer LDS-1G (Detuo Electron, Shanghai, China), the drying device is a microwave vacuum drying oven RWBZ-08S (Surui Group, Nanjing, China), and the working frequency is 2450 MHz, the cavity size is 320 × 340 × 250 mm^3, and the maximum microwave power is 800 W, rice weight was measured by Huachao Digital Balance HC Huachao Hi-Tech (Hochoice, Shanghai, China).

The cavity was modeled with reference to the microwave vacuum drying oven used in the experiment, as shown in Figure 1. The model includes a microwave cavity, waveguide, etc. For the 100 g rice sample used in the experiment, in order to reduce the complexity of modeling, the grain heap was simplified to a cylindrical homogeneous body. The finite element software COMSOL (V5.6a, COMSOL Inc. Stockholm, Sweden) was used to solve the conservation of energy equations. The 60 s microwave

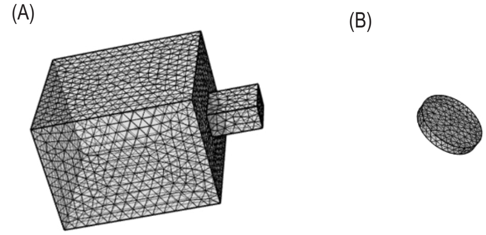

Figure 1. Finite element mesh generation. (A) Meshing scheme for cavity and (B) Meshing scheme for sample.

vacuum heating simulation calculation was carried out under the vacuum degrees of 0.02 MPa, 0.04 MPa, and 0.06 MPa, to obtain the temperature field distribution during the drying process of the rice.

In order to verify the accuracy of the moisture content variation equation in the microwave vacuum drying process and understand the moisture change law during the drying process, microwave vacuum drying experiments were carried out on rice. Take the rice of the same variety, select the rice with entire grains and without any damages, soak it in water, dry it, and use the grain moisture meter to measure the moisture content. After it reaches the required moisture content, weigh 100 g into a beaker, spread it out, and place it in a microwave vacuum drying oven. Set the vacuum to 0.02 MPa, 0.04 MPa, and 0.06 MPa, and the maximum drying temperature is limited to 40°C, dry each group for 1 h. Weigh the weight every 4 min and calculate the moisture content. Fit the experimental data of rice moisture content under different vacuum degrees and compare them with the calculated values to verify the accuracy of the model and analyze the influence of different vacuum degrees on the rice drying rate.

Law of mass and heat transfer

The drying process of rice can be regarded as the process of energy transmission and water migration of porous media. Every grain of rice is a mixture of solid, liquid, and gas. Free water can be transferred to the surface through water migration, and combined water can be transported to the surface of the material through local evaporation and diffusion. Therefore, water transport in the drying process includes free water migration, water vapor permeation, water vapor diffusion, and combined water diffusion.

In order to facilitate the establishment of the porous media transport model during the drying process, the following assumptions are adopted (Dai *et al.*, 2020; Teleken *et al.*, 2020; Wu *et al.*, 2020): (1) The capillary of the porous material is rigid, and the sample does not undergo chemical reactions; (2) Each phase is in local thermodynamic equilibrium; (3) the gas phase is ideal in the sense of thermodynamics; (4) Darcy's law applies to liquid and gas phases; (5) In the liquid and gas phases, the influence of gravity is ignored; (6) The permeability of liquid and gas can be expressed by the relative permeability; (7) Under macroscopic conditions, it is assumed that the sample is uniform and isotropic; (8) The nonthermal effects of microwave radiation can be ignored; (9) The deformation of the material during the drying process is not considered.

The porosity of rice (ϕ) is defined as the ratio of pores to the total volume of rice:

$$\varphi = \frac{V_{\mathrm{w}} + V_{\mathrm{g}}}{V} \tag{1}$$

Where, V_w and V_g are expressed respectively as the volume occupied by liquid water and gas, m^3, and V is the total volume of the rice sample, m^3.

For the pores of each volume element in rice, the water saturation (S_w) and gas saturation (S_g) are defined as the volume fraction of liquid water and gas relative to the total volume of the pores, respectively:

$$S_i = \frac{V_i}{\varphi V},\ i = \mathrm{w,g} \tag{2}$$

Mass conservation equation

During the rice heating and drying process, the mass conservation equation of the material transfer process can be expressed as follows (Selimefendigil *et al.*, 2021):

$$\begin{cases} \dfrac{\partial c_{\mathrm{w}}}{\partial t} + \nabla \cdot \overline{n}_{\mathrm{w}} = -I_w \\ \dfrac{\partial c_{\mathrm{g}}}{\partial t} + \nabla \cdot \overline{n}_{\mathrm{g}} = I_w \\ \dfrac{\partial c_{\mathrm{v}}}{\partial t} + \nabla \cdot \overline{n}_{\mathrm{v}} = I_w \end{cases} \tag{3}$$

Where, c_{w}, c_{g} and c_{v} are the mass concentrations of water, gases, and vapors, respectively, kg/m$^{3;}$ $\overline{n}_{\mathrm{w}}$, $\overline{n}_{\mathrm{g}}$, and $\overline{n}_{\mathrm{v}}$ are the mass flux of water, gas, and vapor phases, respectively, m^2/s; and I_w represents the phase change of free water.

During the drying of agricultural products, nuclear magnetic resonance shows that the free water decreased very fast in the initial stage. Combined water also experienced a similar rapid decline in the later stage (Lv *et al.*, 2018), and therefore, the combined water migration process needs to be considered in the drying process. The mass conservation equation mainly includes three forms: the migration of free water, and the permeation and diffusion of combined water and water vapor. Because vacuum microwave drying is used in this study, the quality change caused by airflow can be ignored. Then, the mass conservation equation can be expressed as:

$$\begin{cases} \dfrac{\partial c_{\mathrm{w}}}{\partial t} + \nabla \cdot \overline{n}_{\mathrm{w}} = -I_w \\ \dfrac{\partial c_{\mathrm{g}}}{\partial t} + \nabla \cdot \overline{n}_{\mathrm{g}} = 0 \\ \dfrac{\partial c_{\mathrm{v}}}{\partial t} + \nabla \cdot \overline{n}_{\mathrm{v}} = I_w + I_{\mathrm{b}} \\ \dfrac{\partial c_{\mathrm{b}}}{\partial t} + \nabla \cdot \overline{n}_{\mathrm{b}} = -I_{\mathrm{b}} \end{cases} \tag{4}$$

Where, c_b is the mass concentration of the combined water, kg/m^3; $\bar{n}_b$ is the mass flux of the combined water, m^2/s; and I_b represents the phase change of the combined water. The relationship between mass concentration and moisture content can be expressed as follows (Li *et al.*, 2008):

$$C=\rho M \tag{5}$$

In the drying process, free and combined water leave the rice after evaporating. Combining Equations 4 and 5, the rice quality conservation equation is expressed as:

$$\frac{\partial M}{\partial t}+\nabla\cdot\left(\frac{\bar{n}_w+\bar{n}_v+\bar{n}_b}{\rho_s}\right)=0 \tag{6}$$

Where, ρ_s is the rice density, kg/m^3.

The process of migration of free water is mainly driven by the pressure gradient generated during the internal drying process of the rice. According to Darcy's law, the seepage velocity is directly proportional to the pressure gradient in the medium, so the free water migration flux in the rice can be expressed as follows (El-Maghlany *et al.*, 2019):

$$\bar{n}_w=-\rho_w\frac{k_w}{\mu_w}\nabla P \tag{7}$$

Where, μ_w is the viscosity of the liquid phase, Pa·s; k_w is the permeability of water, m^2; ρ_w is the density of water, kg/m^3; and P is the total pressure of the gas phase, Pa.

For a mixture of air and steam, Dalton's law states that the total pressure of the gas phase is equal to the sum of the partial pressures of steam and air. At the same time, under capillary pressure, the transfer of water out of the pores is hindered, and the pressure of free water in the pores can be expressed as (Vu and Tsotsas, 2019):

$$P=P_v+P_a-P_c \tag{8}$$

Where, P_v is the partial pressure of steam in the capillary, Pa; P_a is the ambient pressure, Pa; and P_c is the capillary pressure, Pa.

From Equations 7 and 8, it can be seen that the free water migration flux can be reduced to:

$$\bar{n}_w=-\rho_w\frac{k_w}{\mu_w}\nabla\left(P_v+P_a-P_c\right) \tag{9}$$

In porous media, capillary pressures of different magnitudes are generated when the liquid content changes. The capillary pressure causes the liquid to be subjected to negative pressure, thereby affecting the free water migration. The capillary pressure is related to the moisture content and temperature of the material, which can be expressed as (Khan *et al.*, 2018):

$$p_c=\sqrt{\frac{\varphi}{k}}\times(0.1212-0.000167T)\times\left\{0.364[1-\exp(40S_w-40)]+0.221(1-S_w)+\frac{0.005}{S_w}\right\} \tag{10}$$

Where, k is the inherent permeability, m^2; and T is the temperature, K.

The evaporation of the liquid during the drying process will increase the gas phase pressure, thereby promoting the penetration of water vapor, and the capillary vapor pressure generated by the evaporation is given by the Kelvin equation (Chaiyo and Rattanadecho, 2013):

$$P_v=P_{v,sat}(T)\exp\left(\frac{p_c}{\rho_v RT}\right) \tag{11}$$

Where, $P_{v,sat}(T)$ is the saturated vapor pressure, Pa.

The rate of evaporation of liquid water to steam during the rice drying process can be expressed by the nonequilibrium equation (Kumar *et al.*, 2018):

$$I_w=\frac{KM\varphi S_w\left(p_{v,eq}-p_v\right)}{RT} \tag{12}$$

Where, K is the evaporation rate constant, 1/s; $P_{v,eq}$ is the equilibrium vapor pressure of water, Pa.

For porous media, the equilibrium vapor pressure at a specific moisture content and temperature can be represented by a moisture isotherm (Joardder *et al.*, 2017):

$$P_{v,eq}=P_{v,sat}(T)\exp\{-0.182M^{-0.696}+0.232\exp(-43.949M)M^{0.0411}\ln[P_{v,sat}(T)]\} \tag{13}$$

Water vapor is mainly eliminated by permeation and diffusion, and its fluidity depends on the pressure of the gas phase and the water vapor concentration gradient. Then the vapor phase mass flux can be expressed by Darcy's law and Fick's law of diffusion (Selimefendigil *et al.*, 2020):

$$\bar{n}_v=-\rho_v\frac{k_v}{\mu_v}\nabla P_v-\rho_v D_v\nabla M_v \tag{14}$$

Where, ρ_v is vapor density, kg/m^3; k_v is vapor permeability, m^2; μ_v is steam viscosity, Pa·s; D_v is water vapor diffusion coefficient, m^2/s; M_v is vapor content.

During the drying process, the combined water diffuses driven by the concentration gradient and the thermal gradient (Selimefendigil *et al.*, 2021). Considering that the rice drying process takes a long time and adopts constant temperature drying, the effect of thermal gradient in the drying process can be ignored. The combined water quality flux can be described by Fick's second law:

$$\bar{n}_b = -D_b \nabla c_b \tag{15}$$

Where, D_b is the combined water diffusion coefficient, m^2/s.

Energy conservation equation

The electromagnetic distribution in the microwave heating cavity can be analyzed by the Maxwell equation (Wang *et al.*, 2020):

$$\nabla \mu_r^{-1}(\nabla \bar{E}) - \left(\frac{2\pi f}{c}\right)^2 (\varepsilon' - j\varepsilon'')\bar{E} = 0 \tag{16}$$

Where, μ_r is the relative permeability; $\bar{E}$ is the electric field strength, v/m; f is frequency, Hz; c is the speed of light (3.0×10^8 m/s), ε' and ε'' are dielectric constant and dielectric loss respectively, and j is an imaginary number.

Loss of electromagnetic energy and dielectric loss is proportional to the square of the electric field intensity:

$$Q = \frac{1}{2}\omega\varepsilon_0\varepsilon'' |\bar{E}|^2 \tag{17}$$

Where, Q is the lost power, w/m^3; ω is the angular frequency, rad/s; ε_0 is the dielectric constant of free space. The initial conditions of all variables are listed in Table 1 (Fan *et al.*, 2014; Pham *et al.*, 2020; Teleken *et al.*, 2020).

The temperature changes in the microwave vacuum drying process can be described by the energy conservation equation. The energy conservation equation includes heat conduction, evaporative cooling, and microwave heat source terms (Autengruber *et al.*, 2020), there are three forms of solid, liquid, and gas in the drying process of porous media, and the three are at the same temperature at the same place, so it is only necessary to list the following energy conservation equation for the drying medium (Li *et al.*, 2019):

$$\rho_{eff} C_{p,eff} \frac{\partial T}{\partial t} = \nabla\left(k_{eff} \nabla T\right) - \lambda_h I + Q \tag{18}$$

Where, λ_h refers to evaporation latent heat, J/kg; physical properties of the mixture can be obtained by the physical properties of the average of the components of the object; ρ_{eff}, $C_{p,eff}$ and k_{eff} respectively refers to the density weighted mixture, kg/m^3, specific heat capacity, J/(kg·K),

Table 1. Initial condition and material properties applied in model.

Parameter	Value
Microwave frequency f/GHz	2.45
Output power/W	400
Pressure, P (kPa)	101.325
Temperature, T_0 (K)	293.15
Dielectric constant	
water	$86.5 - 0.33\,(T - 273.15)$
solid	51.4
gas	1
Loss constant	
water	$13.4 - 0.13\,(T - 273.15)$
solid	$0.001T^2 - 0.224T + 17.133$
vapor	0
Density	
water, ρ_w (kgm^{-3})	998
vapor, ρ_v (kgm^{-3})	Ideal gas
solid, ρ_s (kgm^{-3})	1185
Viscosity	
water, μ_w (Pas)	$2.74 \times 10^{-6}\exp(1735.5/T)$
vapor, μ_v (Pas)	$0.017 \times 10^{-3}\exp(T/273)^{0.35}$
Evaporation constant, K (1/s)	100
Latent heat of change phase of water, λ_h (J/kg)	2.36×10^6

Thermal conductivity, W/(m·K), weighted by volume fraction, or mass fraction (Pham *et al.*, 2020):

$$\begin{cases} \rho_{eff} = \varphi\left(S_g\rho_g + S_w\rho_w\right) + (1-\varphi)\rho_s \\ C_{p,eff} = \varphi\left(S_g C_{pg} + S_w C_{\cdot w}\right) + (1-\varphi)C_{ps} \\ k_{eff} = \varphi\left(S_g k_{th,g} + S_w k_{th,w}\right) + (1-\varphi)k_{th,s} \end{cases} \tag{19}$$

Where, $k_{th,g}$, $k_{th,w}$, *and* $k_{th,s}$ represent the thermal conductivity of gas, water, and solid, respectively, W/(m·K); C_{pg}, C_{pw}, C_{ps} represent specific heat of gas, water, and solid, respectively, J/(kg·K).

In the drying process, the surface of the rice mainly takes away heat by convection heat transfer, so the boundary heat loss can be expressed as (Vu and Tsotsas, 2019):

$$q_{surf} = h_T\left(T - T_{air}\right) \tag{20}$$

Where, h_T is the convective heat transfer coefficient, W/(m^2·s); T_{air} is the room temperature, K.

Results and Discussion

Figure 2 shows the diffusion and migration of moisture during the drying process. As the temperature increases, the capillary pressure will gradually decrease, which increases the free water migration during the drying process, thereby promoting the reduction of water content

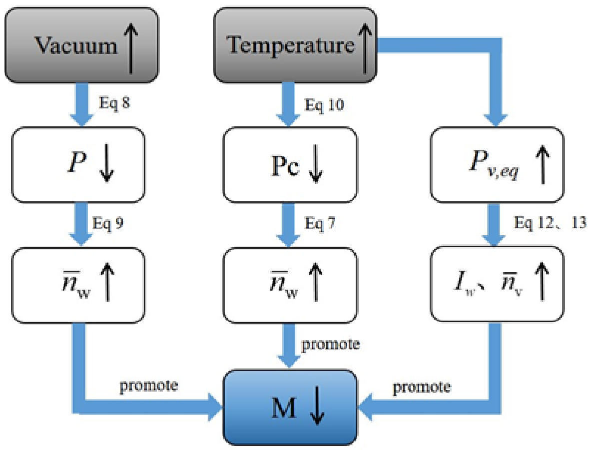

Figure 2. Diffusion and migration of moisture during drying.

in rice. Moreover, with the increase of temperature, the equilibrium vapor pressure will gradually increase, which will increase the gasification speed and water vapor migration in rice, thereby promoting the reduction of rice moisture content. For the effect of vacuum degree, the higher the vacuum degree, the stronger the external negative pressure on the free water inside the rice, which will promote the migration of free water inside the rice, thereby accelerating the reduction of water content in the rice.

Temperature changes during rice drying

The microwave heating simulation of rice was carried out under different vacuum degrees, after 30 s, 45 s, and 60 s. The results of the solution of the temperature field are shown in Figure 3. It can be seen from the figure that the temperature distribution of the grain pile shows a

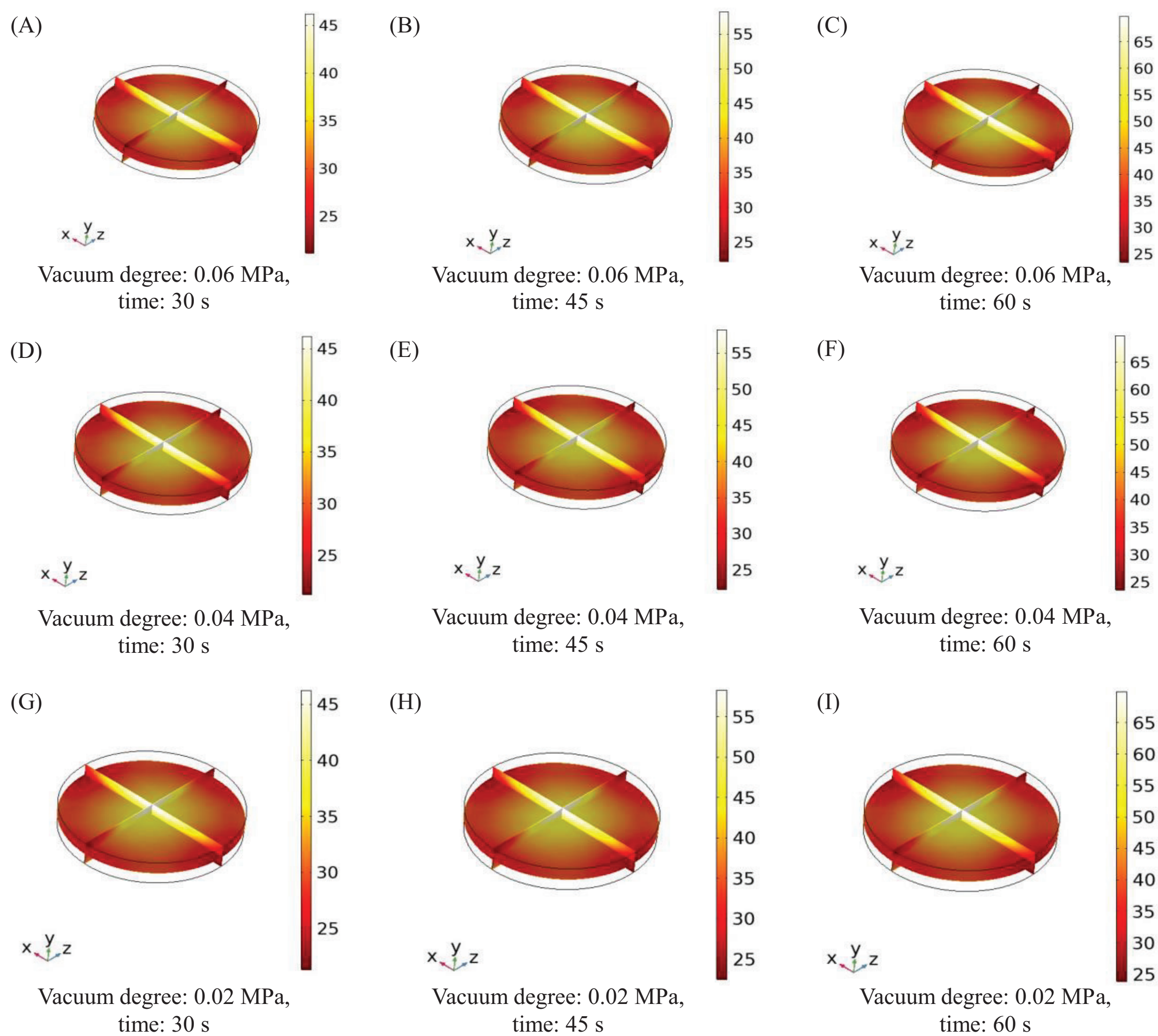

Figure 3. Simulated temperature distribution of rice pile under different vacuum and drying time.

trend of high center point and low surroundings. This is because the heat of the central portion is not easily sent out, which produces a hot spot in the microwave chamber (Bhagya *et al*., 2021). And as time increases, the heat gradually spreads to the edge, which indicates that the piled rice grains are heated unevenly during the microwave heating process condition.

The comparison shows that under different pressures, the temperature difference of the rice during the heating process is small, indicating that the degree of vacuum has less influence on the heat transfer process during the drying process of the rice. This finding was in agreement with that of Zhan et al. (2020), who reported that the degree of vacuum has a negligible effect on the drying behavior.

Figure 4 shows the temperature increase curve in the center of the grain pile during microwave heating. At high power density, free water within sample absorbed much microwave energy (Liu *et al*., 2021). It can be seen that the rice temperature increases rapidly with time and that the central point temperature can reach about 52°C when heated for 60 s. Because the temperature rises quickly during the heating process, it is necessary to accurately grasp the heating time during the drying process to prevent excessive temperature from affecting the quality of rice.

From the numerical relationship, it can be seen that at the same time, the temperature of the rice core is the highest when the vacuum degree is 0.06 MPa, and the temperature is the lowest when the vacuum is 0.02 MPa. It can be seen that the higher the vacuum degree, the higher the corresponding temperature at the same time. This is mainly due to the convective heat transfer as the main external conduction method in the drying process of rice. The higher the vacuum, the thinner the air and the weaker the convective heat transfer, resulting in a faster rise in sample temperature.

Changes of capillary pressure during rice drying

For unsaturated porous media, the capillary pressure causes the liquid to be subjected to negative pressure, which has a great influence on moisture migration during the drying process. The capillary pressure of the porous media is related to the ambient temperature and saturation, as shown in Figure 5. At 293.15 K, 303.15 K, 313.15 K, and 323.15 K, the capillary pressure decreases with the increase of saturation. Among them, when the temperature is 293.15 K, the capillary pressure is as high as 400 Pa, and when the temperature is 323.15 K, the capillary pressure is only 372 Pa at the highest point. Under the same saturation, the higher the temperature, the lower the capillary pressure. Standnes *et al.* (2021) reported that the capillary drainage pressure declines with a fractional rate for increasing temperature, which further supported the findings of this study. At the same time, under the same temperature conditions, the capillary pressure gradually decreases as the water saturation of the rice increases.

When the external pressure does not change, as the drying process of the rice goes on, the moisture content will gradually decrease, and the capillary pressure will increase accordingly. Under the action of the capillary pressure, the negative pressure of the liquid will gradually increase, which will gradually reduce the drying rate.

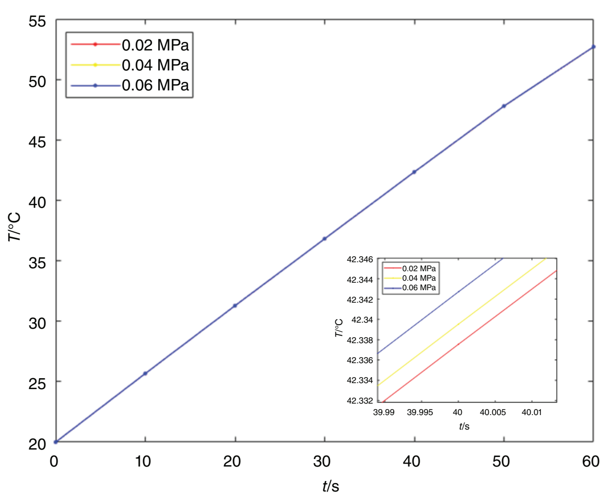

Figure 4. Central temperature curve of rice pile.

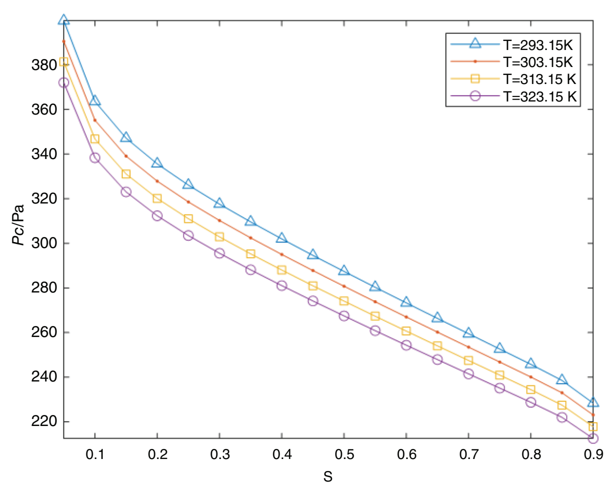

Figure 5. Relationship between capillary pressure and saturation at different temperatures.

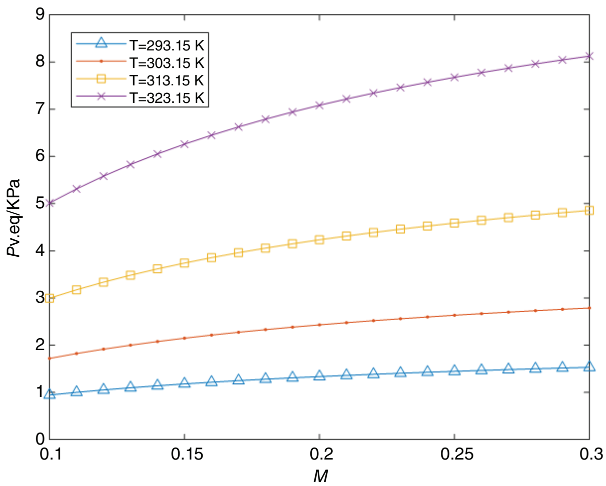

Figure 6. Effect of moisture content on equilibrium vapor pressure at different temperatures.

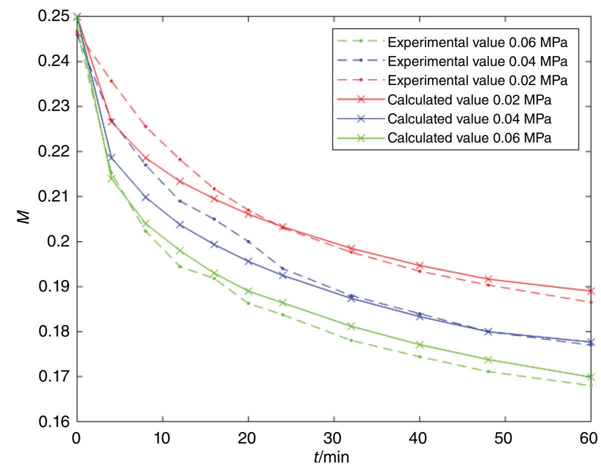

Figure 7. Change of moisture content during drying under different vacuum degrees.

Changes of equilibrium vapor pressure during rice drying

For porous media, the equilibrium vapor pressure at a specific moisture content and temperature can be represented by a moisture isotherm. Figure 6 shows the relationship between equilibrium vapor pressure and moisture content and temperature.

It can be seen from the figure that when the water content is 0.1, at a temperature of 293.15 K, the minimum equilibrium vapor pressure is about 1 KPa, and at a temperature of 323.15 K, the equilibrium vapor pressure can reach 5 KPa. At the same time, at the same temperature, as the moisture content decreases, the equilibrium vapor pressure gradually decreases. When comparing the four curves, it can be found that the higher the temperature, the higher the equilibrium vapor pressure under the same moisture content, which indicates that increasing the drying temperature helps to increase the drying rate.

Changes of moisture content under different vacuum degrees

Figure 7 shows the variation of moisture content with time when rice is dried in the microwave at different vacuum degrees.

After drying the rice for 60 min under the drying conditions of vacuum degrees of 0.02M Pa, 0.04M Pa, and 0.06M Pa, the calculated moisture content decreased from 0.25 to 0.189, 0.177 and 0.169, and the experimental value decreased from 0.25 to 0.186, 0.177, and 0.167. The experimental value was in good agreement with the calculated value. It can also be found from the figure that the moisture content declined rapidly during the first 10 min of the drying process, and as the drying progressed, the declining trend of the moisture content gradually slowdown. These findings are in line with the reports of other authors (Li *et al.*, 2020).

Compared with the experimental value the calculated value decreased faster in the initial stage. This is because the calculated value was set to a temperature of 40°C, and it took a period of heating to reach this temperature during the experiment. Under the conditions of vacuum degree of 0.02 MPa, 0.04 MPa, and 0.06 MPa, respectively, the rice grains showed a slowdown in drying trend, and the higher the vacuum degree, the faster the moisture content decreased, indicating that increasing the vacuum degree has a positive effect on rice drying.

Conclusion

In this article, the law of mass and heat transfer is studied in the process of microwave vacuum drying of rice. Combined with three-dimensional finite element simulation and experimental verification, the characteristic drying parameters are analyzed, and the following conclusions are drawn:

1. The temperature of rice increases relatively rapidly during the microwave heating process, and the degree of vacuum has little effect on heat transfer during the heating process. The overall temperature distribution of the grain pile presents a trend of high center and low surroundings, and the rice was heated unevenly during microwave drying.

2. Through numerical analysis, it was found that the drying rate of rice was different during drying under different vacuum degrees. The calculated value is in good agreement with the experimental value. In the initial stage, the moisture content of rice decreased rapidly. And as the drying progressed, the moisture content continued to decrease, and the drying rate gradually slowed down, showing a trend of decreasing rate.
3. The reason for the decrease in rice drying rate is the change in capillary pressure and equilibrium vapor pressure. As the moisture content of the rice gradually decreases, the capillary pressure inside the rice increases, while the equilibrium vapor pressure gradually decreases. The increase of capillary pressure gradually increases the negative pressure on the liquid inside the rice, and the decrease of the equilibrium vapor pressure leads to the reduction of the water evaporation rate during the drying process, both of which can lead to the decrease of the drying rate.

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Conflict of Interest

No potential conflict of interest was reported by the authors.

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