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# Analysis of the heat transfer characteristics of blackberries during microwave vacuum heating

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ABSTRACT

Microwave vacuum heating of blackberries was carried out to investigate the effects of microwave power and vacuum degree on the temperature of blackberries during the heating process, and the distribution of the temperature field was observed. Using numerical simulations, a combined electromagnetic and heat transfer model was established. The simulations can be used to observe the locations of hot spots and cold spots during heating. The appropriate microwave power and vacuum could also be selected using the simulation to reduce the temperature difference of the locations of hot spots and ensure uniform heating. The results show that, for blackberries heated for 2 min at a microwave power of 400 W and vacuum degree of −80 kPa, the temperature of the hot spot was maintained at about 60 °C and the temperature difference was about 0.27; thus, the heating was uniform, meeting the industrial drying requirements for blackberries.

## 1. Introduction

The blackberry, the berry of plants of the *Rubus* genus in the rose family, Rosaceae, is an important small fruit shrub. Blackberry plants were naturalized in China in 1986, and the promotion of blackberries began in 1994. By 2010, the blackberry planting area had reached more than 4500 ha in China, the largest planting base in Asia, and is famous throughout the world, accounting for about one-fifth of the world's acreage of blackberry plantation (Carlos et al., 2015). Blackberries are rich in nutrients and their taste is unique. Consequently, they are popular with consumers. In addition, because blackberries contain anthocyanins, they have health benefits, which can promote the regeneration of retinal rhodopsin and improve visual acuity. Thus, the plant is widely respected in the medical field (Guan et al., 2002; Elisia et al., 2007). Blackberry fruit reach maturity in midsummer. Fresh blackberries are soft, juicy, and perishable, not resistant to storage and transportation, with a storage time at an ambient temperature of only 2–3 days. Consequently, more than 90% of the fresh fruit is processed and frozen; thus, it is essential to develop quick processing methods for blackberries. At present, the main drying methods used for dehydration are vacuum freeze drying, hot air drying, and microwave drying. Although the quality of the vacuum freeze-drying products is high, the cost of investment is also high. In addition, hot air drying has some problems such as low efficiency. The thermal efficiency of microwave drying is high, but it is difficult to control, easily resulting in overheating that damages the quality of the product, causing burning, surface hardening, and other phenomena (Knoerzer et al., 2008; Song et al., 2015). Microwave vacuum drying is the use of microwave energy for drying materials under vacuum conditions, utilizing the strong penetrating power of microwaves and increasing the internal and external temperature of the material at the same time, resulting in overall heating and shorter drying times. At the same time, a vacuum environment makes the water evaporate rapidly at lower temperatures, allowing the materials to be dried at low temperatures, preventing oxidation and maintaining the antioxidant components of blackberry.

Microwave vacuum drying is better than the hot air drying in terms of the quality of drying, which is similar to that of freeze drying, and is superior to single freeze drying, microwave drying, and vacuum drying in terms of the drying efficiency. Microwave vacuum drying has the advantages of rapid drying, high material quality, and thermal efficiency (Geedipalli et al., 2007; Song et al., 2016).

With the rapid development of computer and computer aided

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**Nomenclature**

| | |
|---|---|
| $E$ | internal electric field (V/m) |
| $\mu_r$ | relative permeability (H/m) |
| $\varepsilon_r$ | relative dielectric constant |
| σ | electrical conductivity (S/m) |
| $\varepsilon_0$ | vacuum dielectric constant (F/m) |
| ω | excitation frequency of the electromagnetic wave (rad/s) |
| $k_0$ | free space vector (rad/m) |
| $P_u$ | dissipated power per unit volume (W/m$^3$) |
| $\varepsilon\varepsilon_0$ | vacuum dielectric constant (8.854 × $10^{-12}$ F/m) |
| $\varepsilon$ | dielectric loss factor of the material |
| $f$ | frequency of the magnetron (Hz) |
| $\rho$ | density of the material (kg/m$^3$) |
| $C_P$ | specific heat capacity at constant pressure (kJ/kg °C) |
| $T$ | temperature at simulation time (°C) |
| $k$ | thermal conductivity (W/m °C) |

| | |
|---|---|
| $D$ | electric displacement vector |
| B | magnetic induction intensity |
| n | steering |
| h | surface convective heat transfer coefficient (W/m. °C) |
| Ta | the initial temperature (°C) |
| p | pressure of the microwave vacuum device (Pa) |
| p' | relative vacuum degree (negative value) (Pa) |
| patm | standard atmospheric pressure (Pa) |
| μ | relative permeability |
| ε′ | dielectric loss factor |
| ε″ | relative dielectric constant |
| σ | conductivity (S/m) |
| ρ | density (Kg/m) |
| $k$ | heat transfer coefficient (W/m °C) |
| $C_p$ | specific heat capacity (J kg °C) |
| $h$ | mesh size (mm) |
| $\lambda$ | free space wavelength |

engineering and efficient numerical simulation, computer simulations have become effective tools to understand the complex microwave vacuum heating process. The establishment of a simulation model means that multiple experiments are no longer required, avoiding the limitations of experimental conditions and speeding up the research cycle. At present, research into the simulation of the temperature field during microwave heating has been reported both at home and abroad (Seeram et al., 2006) using finite element simulation to calculate the transient heating process of the microwave oven with a rotating disk, simulating the heating characteristics of a household microwave oven. Pu et al. (2017) studied the effects of the position of food in combined hot air and microwave heating with a numerical simulation method, and they illustrated the problem of temperature inhomogeneity in microwave heating. In addition, the feasibility of their numerical model was verified by experiment (Pu et al., 2017). However, reports of the numerical simulation study of microwave heating involving a vacuum, where the principles involved are relatively complex, are relatively scant, and the relevant simulation model has not yet been found. Thus, we modeled the microwave vacuum drying process to observe the transient heat transfer characteristics of blackberries and collected comprehensive experimental results to investigate the effects of microwave power and vacuum degree on the temperature of the blackberries during the drying process. This provides a theoretical basis for the improvement of plant fruit and vegetable drying technology and equipment, providing technical support for industry.

## 2. Mathematical physics model of microwave vacuum heating material

A relatively mature method for calculating the microwave heating of a material is the coupling of electromagnetic and heat transfer models. The electromagnetic energy distribution inside the material is determined by Maxwell's equation (Eq. (1)) (Pitchai et al., 2014).

$$\nabla \times \mu_r^{-1}\left(\nabla \times \vec{\boldsymbol{E}}\right) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\vec{\boldsymbol{E}} = 0 \tag{1}$$

Here, $\vec{E}$ is the internal electric field strength in the heating material (V/m), $\mu_r$ and $\varepsilon_r$ are the relative permeability and the relative dielectric constant of the material, respectively, $\sigma$ is the electrical conductivity of the material (S/m), $\varepsilon_0$ is the vacuum dielectric constant (F/m), ω is the excitation frequency of electromagnetic wave (rad/s), and $k_0$ is the free-space vector (rad/m).

An electromagnetic wave loses its energy while traveling through a lossy dielectric medium such as fruits and vegetables. Part of the electromagnetic power is converted into thermal energy within the material. The conversion of electromagnetic energy into thermal energy is proportional to the dielectric loss factor and the square of the electric field strength (Eq. (2)) (Pitchai et al., 2014).

$$P_v = \pi f \varepsilon_0 \varepsilon'' \left|\vec{E}\right|^2 \tag{2}$$

Here, $P_v$ is the dissipated power per unit volume (W/m$^3$), $\varepsilon_0$ is the vacuum dielectric constant (8.854 × $10^{-12}$ F/m), $\varepsilon''$ is the dielectric loss factor of the material, and $f$ is the frequency of the magnetron (Hz).

The dissipative power is determined by the Fourier equation shown in Eq. (3).

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + P_v \tag{3}$$

where $\rho$ is the density of the material (kg/m$^3$), $C_P$ is the specific heat capacity at constant pressure (kJ/kg °C), $T$ is the temperature at simulation time $t$ (°C), and k is the thermal conductivity (W/m °C).

The dielectric properties of the materials can be characterized by the dielectric constant and dielectric loss factor, as shown in Eq. (4).

$$\varepsilon_r = \varepsilon'_r - j\varepsilon''_r = \varepsilon'_r(1 - jtan\delta) \tag{4}$$

Here, $\varepsilon''_r$ is the loss of the electromagnetic energy of the material itself, which can also be expressed by the loss tangent of the material (Eq. (5)).

$$tan\delta = \varepsilon_r''\Big/\varepsilon_r' \tag{5}$$

When the heating material is an isotropic linear medium, Eq. (6) is satisfied (While et al., 2006; Pu et al., 2017).

$$\vec{D} = \varepsilon_r\varepsilon_0\vec{\boldsymbol{E}}\ \ \vec{B} = \mu_r\mu_0\vec{H}\ \ \vec{J} = \sigma\vec{\boldsymbol{E}} \tag{6}$$

Here, $D, B, J,$ and $H$ are the electric displacement vector, magnetic induction intensity, current density, and magnetic field intensity of