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Research Article

Characteristics of Microwave Vacuum Baking and Drying of Oolong and Its Kinetic Model

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Abstract: This paper studies the characteristics of microwave vacuum baking and drying of oolong and analyzes the influence of microwave power and vacuum degree in the drying process on the moisture in the tea. According to the variation law of moisture, it explores the relationship between time and wet base moisture contents under different microwave powers and vacuum degrees, as well as the kinetic mathematical model of vacuum drying for oolong using the microwave. Based on the energy balance between the sensible heat, latent heat and the absorptive microwave energy, this model builds verification test by a large number of experimental data and the results indicate that within certain range of radiation power and thickness, the temperature and moisture content of oolong are uniformly distributed, even more uniform especially in the drying period; generally, the temperature distribution within the oolong fails to show integrity. The free water and water vapor may flow as permeate stream in the internal part of oolong under the action of pressure gradient. The migration intensity mainly depends on the intensity of microwave radiation and initial moisture content; the mathematical model established on this basis could better simulate the microwave vacuum drying process of oolong. Due to its high simulation accuracy, it can be used to describe the variation of moisture content with the drying time and power. The test results provide a technical basis for the controllable industrial production of oolong baking.

Keywords: Drying characteristics, kinetic model, microwave vacuum baking, oolong

INTRODUCTION

Microwave vacuum drying is a combination of microwave and vacuum drying, which means to conduct microwave drying in a vacuum environment. It can not only increase the drying rate but also reduce the temperature, thereby keeping the original nutrients in the food and other raw materials and improving the drying quality of the product (Li, 2005). There are various factors affecting the drying kinetics, among which, the microwave vacuum parameters include microwave power and vacuum degree (Durance and Wang, 2002; McMinn, 2006). Microwave power directly affects the heating rate of the material, which may impact the drying effect. In a process of microwave vacuum drying, the degree vacuum determines the evaporation temperature and evaporation speed of moisture in the material, which may directly influence the drying rate and product quality (Wang, 2002). The microwave vacuum drying technology is a new combination with the development of microwave drying technology. It could dry materials at low temperature, which better maintains their nutritional content as well as the drying quality and overcomes the disadvantage of low conventional heat conduction rate in the vacuum state, thus greatly shortening the drying time and improving the production efficiency. Currently, it is still difficult to achieve online test for the moisture content in the dry production process, so researches on the drying characteristics and kinetic model is of great significance for the optimization and control of the drying process (Giri and Suresh, 2005). Wu *et al*. (2010) have a study on the temperature correlation of ultrasonic attenuation coefficient in microwave hyperthermia.

This study applies the microwave vacuum drying technology in oolong to conduct in-depth study of the microwave vacuum drying characteristics of oolong. Then the kinetic model is established for it to quantify the relationship between the specific power, drying time and the rate of water loss, thereby providing a technical basis for the controllable industrial production of oolong baking.

MATERIALS AND METHODS

Material selection: The fresh leaves of oolong from Xiang hua of Anxi County (the Tieguanyin variety) are selected.

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Instruments: SLK-200 electric thermostat blast oven (Fujian Yun He Tea Machinery Co., Ltd.); microwave vacuum drying oven YH-100-5 kW (Fujian Yun He Tea Machinery Co., Ltd.); tea drier 6LH-70 (Jiayou tea machinery Factory, Anxi County, Fujian province); precision analytical balance PL202-S100 (Mettler-Toledo instrument Co., Ltd. in Shanghai); electronic analytical balance AB204-N (Mettler-Toledo instrument Co., Ltd. in Shanghai).

Test and measurement method:

Preprocessing of fresh leaves of oolong: Fresh leaves of oolong (moisture content 70~75%) →spread out for 3h →steaming (100°C, 60 s) →dynamic dehydrated using tea baker (conduct dehydration for 60 s at 120°C and then 180 s at 80°C) →cooling it to the ambient temperature →rolling →stand by.

Drying conditions: The vacuum degree is 0.04 MPa and the density of microwave radiation power is 115 kwzm^3 (10 sec in 2 min).

Test procedures: Place the specimen in a microwave drying apparatus, then start the vacuum pump and turn on the time controller of microwave oven when the vacuum degree reaches the set value. Conduct the drying test and record the temperature of oolong at the 1.5 min moment of each radiation cycle until this process ends.

Determination of moisture content: Moisture content is determined according to the Determination of Moisture Content of Tea GB/8304-2002.

Data processing: SAS software is used to conduct model fitting and regression analysis.

METHODOLOGY

To establish the model of heat and mass transfer in the drying process for oolong aims to facilitate the prediction and analog control of its actual drying process. The online precise detection of its moisture content during the drying process has been a tough problem, particularly when it is carried out under the condition of microwave and vacuum. Due to the presence of the microwave field, it is difficult to achieve the online detection of its moisture content. In this way, the prediction and effective control for its drying process using the model is of prominent significance. In view of this, based on the mechanism of moisture and heat transfer in oolong, this chapter establishes a mathematical model of heat and mass transfer or oolong under microwave, vacuum and drying condition through mathematical deduction. It could provide a theoretical basis for the analog control of its drying process. The electron micrograph of the cross section of oolong is as shown in Fig. 1.

In the process of microwave drying with higher intensity, the moisture of oolong transfers in the form of permeate stream under the effect of total pressure difference. Free water and water vapor transfer by the wide capillary tube composed by the continuous pits on the cell chamber-cell wall and its migration form is the permeate stream under the effect of total pressure difference. As is shown in Fig. 2, the absorbed water and water vapor coexist in the internal part of tea and they also transfer in the wide capillary tube composed of the continuous pits on the cell chamber-cell wall in the form of water vapor and its moisture migration rate could be solved by the moisture migration equations. In the first phase of drying process, the free water transfers to the evaporating surface affected by the capillary tension difference, so the smaller distance from the evaporating surface indicates the less free water remaining in the cell cavity ending of oolong, coupled with the decrease in its capillary radius, which leads to the absolute increase of the negative moisture potential. Therefore, there exists the gradient that drives the free water transferring from the internal part of oolong to the evaporating surface and its flow rate can be expressed by Darcy's law.

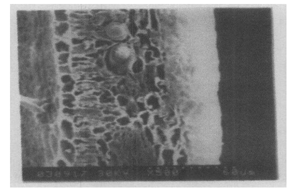

Fig. 1: SEM of tea

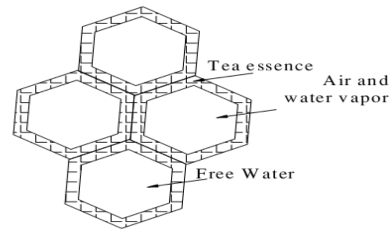

Fig. 2: Migration schematic diagram of free water

Oolong can be regarded as a multiphase system composed of the essence of oolong, free water, absorbed water and water vapor. The energy conservation equation of each component is shown as follows:

Free water:

$$\frac{\partial (C_l h_l)}{\partial t} = \nabla (\lambda_l \nabla T) + q_l - m_l r_l - div\,(h_l \rho_l v_l) \tag{1}$$

Absorbed water:

$$\frac{\partial (C_b h_b)}{\partial t} = \nabla (\lambda_b \nabla T) + q_b \tag{2}$$

Water vapor:

$$\frac{\partial (C_v h_v)}{\partial t} = \nabla (\lambda_v \nabla T) + q_v - div\,(h_v \rho_v v_v) \quad (3)$$

The essence of oolong:

$$\frac{\partial (C_s h_s)}{\partial t} = \nabla (\lambda_s \nabla T) + q_s \quad (4)$$

C_l, C_b, C_v, C_s respectively represents the free water, adsorbed water, concentration of water vapor and oolong density, kg/m^3 wet oolong tea; h_l, h_b, h_v, h_s respectively stands for the specific enthalpy of free water, absorbed water, water vapor and the essence of oolong, J /Kg; v_l, v_v respectively refers to the mobility of free water and water vapor, m/s; ρ_l, ρ_v respectively represents the density of free water and water vapor, kg/m^3; λ_l, λ_b, λ_v, λ_s respectively refers to the thermal coefficient of free water, absorbed water, water vapor and the essence of oolong; q_1, q_b, q_v, q_s, respectively represents the microwave power density of free water, absorbed water, water vapor and the essence of oolong per unit volume, W/m^3 or J/m^3 s; m_l is the evaporation rate of the free water per unit volume, kg/m^3 s; r_l is the vaporization potential of free water, J/kg; T is the temperature of wet oolong, °C. Various items on the left side of the Eq. (1), (2), (3) and (4), respectively represents the energy variation (J/m^3 s) of free water, adsorbed water, water vapor and essence of oolong per unit volume and per unit time. The first item on the right side of the equations represents the heat loss of each component caused by conduction and the second item refers to the microwave energy absorbed by each component in oolong. The third item on the right side of Eq. (1) refers to the heat loss caused by the evaporation of free water. The last item on the right side of Eq. (1) and (3), respectively represents the heat loss caused by the evaporation of free water and water vapor.

Integrate and simplify these four equations to obtain the unified energy conservation equation of wet oolong:

$$\frac{\partial (C_l h_l + C_b h_b + C_v h_v + C_s h_s)}{\partial t} = \nabla (\lambda_{eff} \nabla T) + q - m_l r_l - div\,(h_l \rho_l v_l) - div\,(h_v \rho_v v_v) \quad (5)$$

The first term on the left side of the equation $C_l h_l + C_b h_b + C_v h_v + C_s h_s$ refers to the total energy per unit volume of wet oolong (enthalpy), which can be expressed as:

$$C_l h_l + C_b h_b + C_v h_v + C_s h_s = h\rho \quad (6)$$

And:

$$h = c_p T \quad (7)$$

where,

ρ = The density of the wet oolong, kg/m^3
h = Its specific enthalpy, J/Kg
C_p = Its specific heat, J/Kg °C
T = To its temperature, °C
λ_{eff} = Its effective thermal conductivity, W/m^3 °C
q = The microwave power density absorbed by wet oolong W/m^3

Whose level is the sum of microwave energy absorbed by each component in oolong:

$$q = q_l + q_b + q_v + q_s \quad (8)$$

Generally, the fluid motion of oolong in the drying process is sufficiently slow (moisture with various forms of). Liquid, essence of tea and other components have the same temperature, so the above equation is simplified to the following one:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla (\lambda_{eff} \nabla T) + q - m_l r_l - (c_{pl} \rho_v v_\upsilon + c_{pv} \rho_v v_\upsilon) \frac{\partial T}{\partial x} \quad (9)$$

where in, c_{pl}, c_{pv}, respectively represents the specific heat of free water and water vapor, J/kg °C.

If the thermal migration caused by moisture migration can be ignored, the above equation can be further simplified to the following one:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla (\lambda_{eff} \nabla T) + q - m_l r \quad (10)$$

Previous studies have shown that the microwave drying or the drying combined vacuum and microwave are generally suitable for the tea with lower moisture content. Taking into account the actual situation and the simplification of the model, the mathematical simulation is only carried out for the microwave vacuum drying process of oolong with the moisture content below the critical standard.

ANALYSIS METHODS

The drying process of oolong is one-dimensional unsteady heat and moisture migration process. It needs to transform the equations into algebraic equations in order to solve the differential equations in theory. In this study, finite difference method is used to transform heat and mass transfer equations within the oolong and boundary equations. Figure 3 and 4 shows the mathematical simulation and the actual measurement results of changes in temperature and moisture of oolong in the microwave vacuum drying process. A lot of valuable information can be obtained from the figure. The simulation curve of temperature and moisture changes can be clearly divided into three phases, namely temperature simulation curve which can be divided into early rapid heating section, the

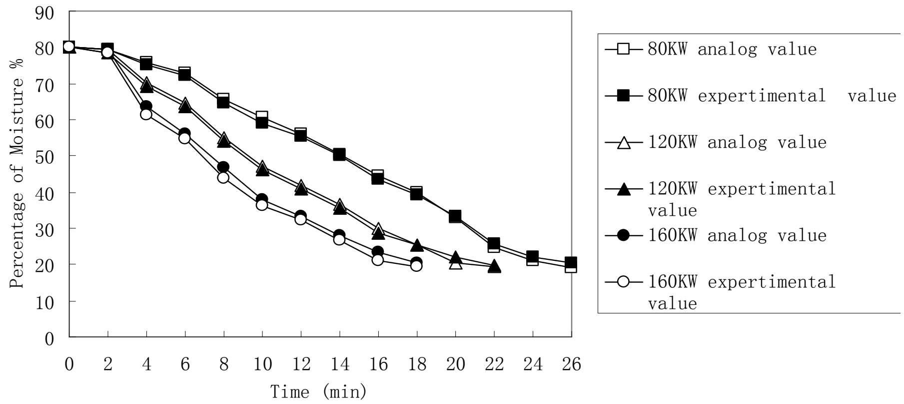

Fig. 3: The comparison of experimental results and calculated results with different microwave power input levels (percentage of moisture)

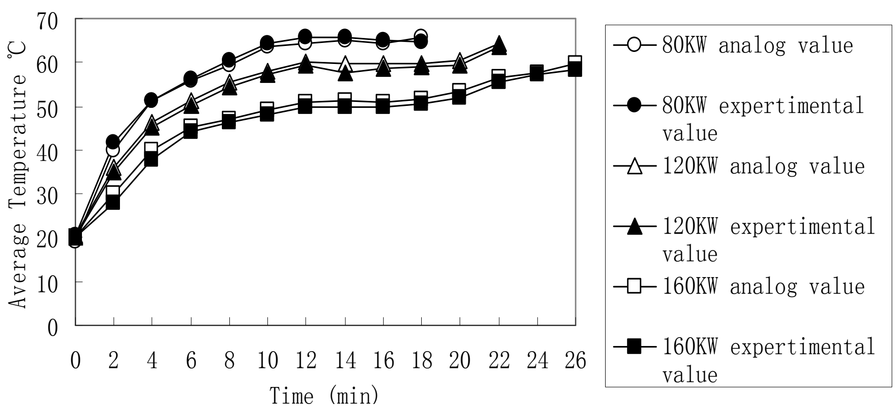

Fig. 4: The comparison of experimental results and calculated results with different microwave power input levels (average temperature)

thermostat section and late warming section, while moisture simulation curve can be divided into the accelerated drying section, constant drying section and decelerated drying section. Especially for temperature simulation curve, the dividing line of the three phases is very obvious. The fitting degree of the simulated curves and experimental test curves of the temperature and moisture reveals that the test measurement is highly correlated to the simulated values. The mathematical calculation results show that the square of the correlation coefficient of the measured and simulated values of oolong moisture is 0.99 and the square of the correlation coefficient between the temperature measurement and simulated values is also up to 0.98, suggesting that the model is with high precision in simulating the microwave vacuum drying process of oolong below the critical moisture.

From the simulation results, we can conclude that the rate is accelerated with the increase in power of microwave radiation and the average temperature of the oolong is elevated, with its drying rate increasing and drying time significantly shortened. Analog curve of microwave radiation power density-Average drying rate of oolong analog curve can be divided into three distinct phases, that is, the accelerated drying of temperature rising section, the thermostat and constant drying section and late decelerated drying section of temperature rising, the greater the radiation power is, the more obvious the dividing line of temperature ranges in temperature simulation curve. Studies have shown that the model can effectively simulate the microwave vacuum drying process of oolong. When drying conditions of oolong change, the relevant parameters in the equation also need to change accordingly. Kinetics test results of tea microwave vacuum drying show that among the many factors that affect the tea microwave vacuum drying rate, only microwave input power density and initial moisture content have a significant impact on the average drying rate of the tea. Therefore, we will conduct mathematical simulation on the drying curve of the microwave radiation power density and the initial moisture content of tea, the experimental results and calculated results are shown in Fig. 3 and 4.

RESULTS AND DISCUSSION

This paper studies the characteristics of microwave vacuum baking and drying of oolong and analyzes the influence of microwave power and vacuum degree in the drying process on the moisture in the tea. The mathematical model is used to conduct mathematical simulation for the microwave vacuum drying process of tea, coupled with the validation for its correctness and accuracy. Researches indicate that the simulated moisture content data is highly correlated to the test data, so is the analog temperature data to the test temperature. The stimulated microwave radiation power and drying characteristics of tea under different initial moisture contents are consistent with the test results. The simulation and test results show that it is feasible to use this model for the mathematical simulation of microwave vacuum drying process of tea, which displays high precision. When tea drying conditions change, the relevant parameters in the equation also need to change accordingly. By mathematical simulation and drying tests, it can be found that the actual drying process, the temperature changes can be used to preliminarily determine the end point of tea drying, which will provide the basis for tea drying process control.

CONCLUSION

Figure 3 and 4 shows the mathematical simulation and the actual measurement results of changes in temperature and moisture of oolong in the microwave vacuum drying process. A lot of valuable information can be obtained from the figure. The simulation curve of temperature and moisture changes can be clearly divided into three phases, namely temperature simulation curve which can be divided into early rapid heating section, the thermostat section and late warming section, while moisture simulation curve can be divided into the accelerated drying section, constant drying section and decelerated drying section. Especially for temperature simulation curve, the dividing line of the three phases is very obvious. The fitting degree of the simulated curves and experimental test curves of the temperature and moisture reveals that the test measurement is highly correlated to the simulated values. The mathematical calculation results show that the square of the correlation coefficient of the measured and simulated values of oolong moisture is 0.99 and the square of the correlation coefficient between the temperature measurement and simulated values is also up to 0.98, suggesting that the model is with high precision in simulating the microwave vacuum drying process of oolong below the critical moisture.

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