Fast Drying of Agriculture Commodities by Using Microwave

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Abstract. Some progress has been made and reported previously due to investigate microwave effects to materials. The microwave applications for material processing by using wide range microwave frequencies such as in sintering, chemical reaction, and drying have been performed. Microwave drying is based on a unique volumetric heating mode with electromagnetic radiation at 2,450 MHz. However, the quest for a what a true microwave effect is still plagued with difficulties. This paper provides a experimental and theoretical analysis of drying materials using microwave. For drying experiments, in this investigation, we were using a domestic microwave oven which operated at three power levels for drying chamber. The samples are agriculture commodity collected from local farmers. The experimental results show that microwave accelerate drying in most materials. The experimental data were analyzed by using an available model constructed from fundamental physics by other scholars. The model has been applied to more understanding the behavior of the microwave drying material.

1. Introduction

Drying of agricultural and food products is one of the most energy intensive processes. These products are dried to inhibit quality decay. The agricultural products are dried after harvest to the moisture content that allows microbial stability during storage [1-2]. For examples, vegetables are blanched before drying to avoid rapid darkening, and drying is not only carried out to inhibit microbial growth, but also to avoid browning during storage. For fruits, the reduction of moisture acts in combination with its acid and sugar contents to provide protection against microbial growth. Other products as crackers are dried beyond the microbial growth threshold to confer a crispy texture, which is liked by consumers. Most farmers use conventional drying method (electric furnace or sun-drying method). In order to improve the performance of these process, new technologies such as microwave heating and a combination of hot air and microwave heating have been used. Their performance and characteristics are evaluated using a mathematical model by scientists. Several theoretical drying models have been developed and most of these models are based on the conventional heat transfer [3].
The application of microwave energy for thermal processing of different materials and substances is a rapidly growing trend of modern science and engineering especially for sintering ceramics [4-10] as well as for drying food [11-13]. In a microwave furnace, the material will absorb microwave energy convert the energy into heat. Heat is generated internally within the materials resulting homogenous heating. The benefit of microwave heating is not only rapid processing but also sometimes improving material properties [14-17]. Experiments of drying characteristics of cocoa bean by using a microwave furnace as well its theoretical analysis have been successfully performed and reported previously as shown in Fig. 1 [12]. The faster reduction of moisture content of samples compared to electric furnace drying result was found. In this paper, experiment results of drying various materials by using a microwave furnace will be presented. From the characteristics of microwave drying of these materials may inform us the role of microwave drying mechanisms.

![Figure 1. Microwave drying of cocoa bean slabs with various microwave power [12]](image-url)

Because drying technology is very important in industrial application, an extensive investigations have been performed by researchers. Several theoretical model have been developed by scholars. The model mostly are based on the conventional heat transfer. Review of model of heat and mass transfer in various systems is compiled by Eckert et al. [18]. Drying models start from the classical liquid diffusion model based on Fick’s law where gradient of liquid content (moisture content) as driving force was reported by Sherwood [19]. King and Harmathy assume that the drying process only based on vapour diffusion [20-21]. Most of the model describe above have not been able to predict drying rates and temperature and moisture content distribution for both hygroscopic and non-hygroscopic materials over a range of boundary conditions. This is because the moisture transport in materials is caused by a variety of mechanisms, each of which is prevalent under different condition. Temperature, the local moisture content and the material properties influence the contribution of each drying mechanism and affect the drying rate. Izume and Hayakawa [22] develop a unique set of heat and moisture equation transfer which are used to model the drying of cylindrical, elastoplastics food. They are solved by the Galerkin’s finite element method and in the time domain by the Crank-Nicholson method. In this paper will be reported experimental results of drying of agriculture commodities by using microwave. Analysis by using available theory was also described.

2. Experimental Method

2.1 Sample preparation

Samples Corn, Coffee, unhulled Rice, and Cacao were collected from local farmers in South East Sulawesi, Indonesia. Prior to drying, samples were selected then washed. All samples then were pellet and cut into slab shape with desired size of 10 mm in diameter and 3 mm in thickness. Silica powder was extracted from rice husk ash where also collected from local farmers. The detail procedure of extraction is published elsewhere [23,24]. Drying experiments were performing by using a microwave oven as well as electric furnace. The electric furnace drying results are used as comparison.

2.2 Drying Experiment

A microwave oven (Panasonic NE-C236, Japan) applied as furnace for drying experiments as shown schematically in Fig. 2. This 2.45 GHz microwave device has maximum output power of 800 W
with power consumption about 1.43 kW. The drying experiments were performed by using three power levels: high power of 600 W, medium power of 300 W and low power of 150 W. The microwave oven equipped by a temperature controlling system with shielded thermocouple. Microwave powers were varied for every samples.

![Schematic picture of a microwave drying system](image)

Figure 2. Schematic picture of a microwave drying system [12]

The moisture content value was determined by using equation:

\[ M(\%) = \frac{(W_t - W_d)}{W_d} \]  \hspace{1cm} (1)

where \( M \) is moisture content, \( W_t \) is the weight of sample (g) at any time and \( W_d \) is the weight of the dried sample.

3. Results and Discussion
3.1 Drying Experiment Results

Drying curves of coffee and corn slabs dried with different methods are presented in Fig. 3 and 4. They shows that the moisture content and drying rate decreased continuously with drying. There are no constant rates drying because most crops as well as coffee exhibit the constant rate drying characteristics at their critical moisture content. Coffee exhibits a constant rate behavior during drying in high moisture content as well as cocoa [1]. However the initial moisture content in this experiment is not up to this range. At the falling rate period the movement of moisture within the coffee to the surface is governed by diffusion since the material is no longer saturated with water. The graph shows that the moisture ratio decreased as the drying time increased. Both graphs also show a faster drying in the microwave drying compared than in the conventional one on all microwave powers.

![Drying curves of coffee slabs (diameter of 10 mm) in a microwave with different microwave power and in an electric furnace (conventional method)](image)

Figure 3. Drying curves of coffee slabs (diameter of 10 mm) in a microwave with different microwave power and in an electric furnace (conventional method)
Figure 4. Drying curves of corn slabs (diameter of 10 mm) in a microwave with different microwave power and in an electric furnace (conventional method)

Generally characteristic of microwave processing of different agriculture materials depend on their physical properties such as moisture content, density, thermal conductivity, and chemical substances as well as temperature. Microwave heating is mainly due to polarization and ionic conduction of water molecules in material. Simplify can be described that the ionic conduction losses and due to dipolar rotation towards microwave frequencies with temperature. The absorption of microwave energy and conversion to heat is due to polarization and conduction would result in a rise in temperature, and this is given by the following equation [25]:

\[
\frac{\Delta T}{\Delta t} = \frac{2\pi f \varepsilon_{\text{eff}} E_{\text{rms}}^2}{\rho cp}
\]

where, \( \varepsilon_0 \) is the permittivity of free space \((8.85 \times 10^{-12} \text{ V/m}^3)\), \( \varepsilon_{\text{eff}} \) is the relative effective dielectric loss due to ionic conduction and dipolar reorientation, \( f \) is the frequency \((\text{Hz})\), \( E_{\text{rms}} \) is the root mean square of the electric field within the material \((\text{V/m})\), \( \rho \) is the bulk density of dielectric material \((\text{kg/m}^3)\) and \( Cp \) is the heat capacity of the material at constant pressure \((\text{J/kg} \cdot ^\circ \text{C})\). The water dipole attempts to continuously reorient in microwave's oscillating field. The dipole lags between the dipole and the field leads to an energy loss by heating. The ease of the movement depends on the strength and extent of the hydrogen bonded network.

Understanding and availability the properties of each materials are important to develop drying model of the materials [26-27]. Some dielectric and thermal properties of various materials at microwaves frequencies provides by Komarov in [28]. The dependency of physical parameters on temperature and moisture content are given in form of analytical equations. For example for Corn is shown in Equation 3 and 4 [28].

\[
\varepsilon'(T) = -0.0005502 T^2 - 0.03792T + 60.68 \quad (5 < T \leq 120)
\]

\[
\varepsilon''(T) = -0.0005502 T^2 - 0.03792T + 60.68
\]

Other materials’data mostly available in Komarov and Hippel [28-29]. By using such equations, the drying path of materials can be control and their quality can be improved.

As comparison for microwave drying material of agriculture commodities, there is shown in Figure 5. Silica ceramic was drying by using 2.45 GHz microwave heating system. Effect of microwave was shown as in agriculture commodities materials.
3.2 Theoretical Analysis of Drying Experiment

The microwave-matter interaction analysis basically can be evaluated from Maxwell’s equations in matter. For microwave drying, the most simple assumption that the absorption rate and the permittivity and permeability of a drying samples are all constant. Thus, Maxwell’s equations are reduced to the telegrapher’s equation which can be solved without reference to the temperature [30]. The temperature variation is calculated by solving the forced heat equation with the forcing term dependent on the square of the amplitude of the electric field. In microwave drying, most of the theoretical work to date has used the simplifying assumption that the amplitude of the electric field is constant. The assumptions made because for materials properties which are temperature-dependent with variable electric field, the forced heat equation and Maxwell’s equation become a highly nonlinear coupled system. The assumptions generally can be applied only for thin materials. One of methods is applied by Ayappa, et al. which predict the temperature profiles in multilayer slabs by simultaneously solving Maxwell’s equation with the heat transfer equation, using the Galerkin finite element method [31].

Another method for modeling the microwave drying material developed by Izumi and Hayakawa [32]. They solve three equations i.e.: heat transfer equation, mass transfer equation, and electromagnetic field equation. The modeling of the heat and mass transfer in food is based on these equations. The equation include all the thermodynamically interactive heat and mass fluxes and mass flux corrections as described follows.

1. **Mass/Moisture Transfer Equation:**

   \[ \frac{\partial C}{\partial t} = \nabla \cdot (D_w \nabla C + D_T \nabla T + D_p \nabla P) \]  

   Where: \( C \) = Volumetric moisture concentration (kg m\(^{-3}\)), \( t \) = time (s), \( D_w \) = mass diffusivity (m\(^2\) s\(^{-1}\)), \( D_T \) = soret mass diffusivity (kg m\(^{-1}\)s\(^{-1}\)K\(^{-1}\)), \( T \) = temperature (K), \( D_p \) = pressure mass diffusivity (kg m\(^{-1}\)s\(^{-1}\)Pa\(^{-1}\)), and \( P \) = water vapour pressure (Pa).

2. **Heat Transfer Equation:**

   \[ c_p \rho_b \frac{\partial T}{\partial t} = \nabla \cdot (k_T \nabla T + k_c \nabla C + k_p \nabla P) + E_{MV} \]  

   Where: \( c_p \) = specific heat (J kg\(^{-1}\)K\(^{-1}\)), \( \rho_b \) = density of dry solid (kg m\(^{-3}\)), \( k_T \) = thermal conductivity (W m\(^{-1}\)K\(^{-1}\)), \( k_c \) = dufour thermal conductivity (W m\(^{-2}\)kg\(^{-1}\)), \( k_p \) = pressure thermal conductivity (W m\(^{-1}\)Pa\(^{-1}\)), and \( E_{MV} \) = internal heat source due to microwave heating.
The $\nabla P$ in the above equation is correlated as follow:

$$\nabla P = \gamma_c \nabla C - \gamma_T \nabla T - \gamma_s \nabla S_v$$  \hspace{1cm} (7)

Where: $S_v$ is volumetric shrinkage coefficient and $\gamma_c, \gamma_T, \gamma_s$ are empirical parameters for relating a static pressure change with vapourised or condensed mass, temperature change and volumetric shrinkage.

For calculating the moisture concentration ($C$), it must be converted to moisture potential to state the moisture transport. This conversion can be using the Gibbs free energy of moisture [23].

$$\phi = \mu_{Gibbs} + RT \ln a_w \hspace{1cm} \text{for } W \leq W_{100\%}$$

$$\phi = \left[\frac{W - W_{100\%}}{W_{100\%} - W_{0\%}} + 1\right] \mu_{Gibbs} \hspace{1cm} \text{for } W > W_{100\%}$$  \hspace{1cm} (8)

Where:

$\phi$ = moisture potential, $a_w$ = water activity, $\mu_{Gibbs}$ = Gibbs free energy of saturated free water (J mol$^{-1}$)

$R$ = universal gas constant (J mol$^{-1}$ K$^{-1}$), $W$ = moisture content (kg water (kg solid)$^{-1}$), $W_{100\%}$ = food moisture content equilibrate to 100% humidity and $W_{0\%}$ = food moisture content equilibrate to 0% humidity. Water activity is function of temperature and moisture so that difficult to estimated. Some people estimated by using the Guggenheim-Anderson-de Bore equation [33]. This method can be applied to the drying experiments in this research. The details will be published in separated paper.

3.3 Electromagnetic Field Equation

The electromagnetic field equations in matter are also based on Maxwell’s electromagnetic theory. However because of complexity of the Maxwell equations in real matter, the assumptions for simplify are always made. For example, the electromagnetic field equation are calculated assuming that a plane electromagnetic wave is propagated in slabs. The slab is divided into layers and each layer has a constant temperature, moisture concentration and constant dielectric properties. This is true may be for thin slab or special materials only. By using these assumptions, the problem become simpler. For example the detail of the calculations and numerical simulation are presented by Tran and Piotrowski based on the following equations [34].

$$N_M = \sqrt{\frac{\varepsilon_M \mu_0}{\mu_0}} \hspace{1cm} N_0 = \sqrt{\frac{\varepsilon_0}{\mu_0}} \hspace{1cm} Y_M = N_M$$  \hspace{1cm} (9)

$$N_i = \frac{\varepsilon_i \mu_0}{\mu_0} \hspace{1cm} Y_i = N_i \sqrt{\frac{\varepsilon_y(1 - S_i)}{\varepsilon_0(1 - S_i) + \varepsilon_{water} S_i}} \hspace{1cm} (10)$$

Where:

$\gamma_i = -\mu_0 \varepsilon_0 \varepsilon_i (2\pi f)^2$

$\varepsilon_i = \varepsilon_{dry}(1 - S_i) + \varepsilon_{water} S_i$

$f$ = frequency of electromagnetic field (Hz), $h_i$ = position of i-th numerical mode from the surface of the sample (m), $S_i$ = relative water content in i-th numerical node, $\varepsilon_0$ = permittivity of vacuum (F m$^{-1}$), $\varepsilon_{dry}$ = relative permittivity of dry material, $\varepsilon_{water}$ = relative permittivity of water, $\mu_0$ = permeability of vacuum.

By using these theories the experiment results can be predicted and controlled so that microwave drying can be more effective. Generally, by using microwave drying agriculture commodities is faster.

4. Conclusion

Experiments of application microwave energy for drying several agriculture commodities have been performed. The microwave showed a faster drying than that of conventional one. Theoretical analysis of the experimental data was performed based on available theories. The application of the microwave energy forces the moisture content gradient and temperature gradient to act together to speed up the drying process. In general, the results in this experiment suggested that microwave technology is appropriate technology for drying agriculture commodities.

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