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# Simulation of microwave thin layer drying process by a new theoretical model

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## HIGHLIGHTS

- A new model was developed and validated to simulate microwave drying.
- Moisture diffusion along material layer was ignored under intensive microwave.
- An optimal layer thickness exists in microwave thin layer drying.
- The temperature gradient has different orientation in hot air and microwave drying.

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## ABSTRACT

Various methodologies have been proposed in literature on modeling microwave drying process. However, in these methodologies moisture diffusion is normally considered in the presence of intensive microwave energy. In the present study, a new theoretical model was developed to simulate microwave drying of thin layer particulate solids, based on the consideration that moisture diffusion along material layer could be ignored due to rapid evaporation under intensive microwave energy. The model was solved numerically by using finite difference method and validated against experimental data. Results indicated good agreement between the model and experimental data, thus providing confidence in the modeling approach. For the system investigated in this study, it was demonstrated that an 80% reduction in drying time was achieved with approximately fivefold increase in microwave power (109–543 W). Furthermore, it was also demonstrated that the drying rate was the maximum corresponding to the optimal layer thickness in microwave thin layer drying process. Qualitative analysis explained the optimal thickness phenomenon using principles of heat and mass transfer. Finally, the validated model was used to predict moisture and temperature distributions along the entire material layer.

## 1. Introduction

Drying is one of the oldest and the most common chemical unit operations, which combines simultaneous heat and mass transfer. It is also one of the most energy-intensive processes due to low energy efficiency in traditional convective hot air drying. For the systems with falling-rate drying characteristics, prolonged drying time may be required for convective drying. Therefore, to overcome this problem dielectric drying, in particular, microwave drying has been given significant attention in recent years. During microwave drying, heat can be produced directly in the entire volume of a material through 'volumetric heating'. Therefore, the heat transfer direction in microwave drying is opposite to that in the traditional convective drying in which heat is transferred from outer thermal medium to the product to be dried. Furthermore, microwave drying process possesses a shorter thermal adjustment time so that drying time can be reduced significantly leading to elevated energy efficiency (Khodabakhshi et al., 2015).

Moisture distribution or drying kinetics in a drying substrate resulting from microwave drying is complicated and fundamentally different from traditional convective hot air drying. Significant research efforts have been devoted to the modeling of the microwave drying process. Models can be broadly classified as empirical fitting, theoretical, and semi-empirical models.

An empirical model is a mathematical equation having parameters to be fitted based on the experimental results, and the definition of its mathematical form does not require the consideration of the theory describing complex heat and mass transfer phenomenon, geometry, and physicochemical characteristics of the product to be dried. Page model (Page, 1949) and Midilli–Kucuk

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## Nomenclature

| | |
|---|---|
| $C$ | specific heat of material (J kg$^{-1}$ K$^{-1}$) |
| $Cp$ | specific heat of water (J kg$^{-1}$ K$^{-1}$) |
| $c_1$ | empirical parameters (K$^{-1}$) |
| $c_2$ | empirical parameters (K) |
| $c_3$ | empirical parameters (–) |
| $D$ | diameter (m) |
| $D_p$ | penetration depth (m) |
| $D_{ls}$ | diffusion coefficient of water (m$^2$ s$^{-1}$) |
| $D_{vs}$ | diffusion coefficient of vapor (m$^2$ s$^{-1}$) |
| $e$ | base of natural logarithm (–) |
| $H$ | material layer thickness (m) |
| $h$ | heat transfer coefficient (W m$^{-2}$ °C$^{-1}$) |
| $h_m$ | mass transfer coefficient (m s$^{-1}$) |
| $M$ | molecular weight (kg mol$^{-1}$) |
| $M.C$ | moisture content on dry basis ((kg water) (kg dry matter)$^{-1}$) |
| $MR$ | normalized moisture content (–) |
| $M_{residue}$ | residual mass of water in material (kg) |
| $M_{total}$ | initial total mass of water in material (kg) |
| $M_v$ | volumetric evaporation rate (kg m$^{-3}$ s$^{-1}$) |
| $m$ | mass (kg) |
| $P_{sv}$ | saturated vapor pressure (Pa) |
| $P_v$ | vapor pressure (Pa) |
| $P_0$ | incident microwave power (W) |
| $P_y$ | absorbed microwave power (W) |
| $Q_{absorbed}$ | absorbed total heat (J) |
| $Q_{mic}$ | microwave heat generation (W m$^{-3}$) |
| $Q_y$ | absorbed microwave energy (W m$^{-3}$) |
| $r$ | evaporation heat (J kg$^{-1}$) |
| $S$ | bottom area (m$^2$) |
| $T$ | temperature (°C) |
| $t$ | time (s) |
| $W$ | moisture content on dry basis ((kg water) (kg dry matter)$^{-1}$) |
| $y$ | height (m) |

*Subscripts*

| | |
|---|---|
| 0 | initial value |
| $e$ | environment |
| exp | experimental |
| *pre* | predicted |
| $v$ | vapor |

*Greek letters*

| | |
|---|---|
| $\beta$ | attenuation (m$^{-1}$) |
| $\varepsilon'$ | dielectric constant (–) |
| $\varepsilon''$ | dielectric loss factor (–) |
| $\lambda$ | thermal conductivity (W m$^{-1}$ °C$^{-1}$) |
| $\lambda_0$ | wavelength in vacuum (m) |
| $\rho_b$ | bulk density (kg m$^{-3}$) |
| $\rho_d$ | density of dried matter (kg m$^{-3}$) |
| $\rho_v$ | vapor density (kg m$^{-3}$) |
| $\varphi$ | relative humidity (–) |
| $\phi$ | material layer porosity (–) |

model (Wang et al., 2016) are the two most frequently used empirical thin layer drying models, which effectively describe drying kinetics in simple systems. For multivariable (multidimensional) system, artificial neural network (ANN) is a more appropriate empirical method (Rodríguez et al., 2014). However, all the empirical models are method- and material-dependent.

In contrast to empirical methods, attempts have been made to modify theoretical methods in order to include every possible transport mechanism for each phase, and describe the mechanisms in a numerical manner. Typical examples are Datta's Multiphase Porous Media Model (Datta, 2007a, 2007b) and other models in which detailed heat and mass transport were considered(Gulati et al., 2015; Hassini et al., 2015; Sun, 2014). This method can provide a detailed moisture distribution. However, besides complex treatment of each mechanism, these models exhibit limitation to describe the drying process in which moisture diffusion plays an important role during mass transfer process.

Semi-empirical methods such as Fick's Second Law (FSL) and Reaction Engineering Approach (REA) are more efficient compared to the above-mentioned approaches. In FSL, moisture and temperature distributions are modeled by coupling heat balance and mass transfer equations (Jumah and Raghavan, 2001; Souraki and Mowla, 2008) assuming that evaporation occurs only at the surface, which is not applicable for internal evaporation under microwave 'volumetric heating'. REA (Putranto and Chen, 2016a, 2016b) is another semi-empirical method to describe drying kinetics based on chemical reaction engineering principles, where drying activity energy is only experimentally evaluated.

In this study, based on the shortcomings of simulation methods existing in literature, a new theoretical model was developed to describe and predict moisture distribution. The key assumption was to ignore moisture diffusion due to rapid evaporation under intense microwave energy thin layer drying process. The main objectives of this study were as follows: (1) development of a new theoretical model for intense microwave thin layer drying process, (2) validation of the model by comparing with experimental data, and (3) prediction of moisture and temperature distribution along the material layer.

## 2. Mathematical model

### 2.1. Problem description

Fig. 1 shows the schematic illustration of an insulated cylindrical container used in this study, with the top surface exposed to the

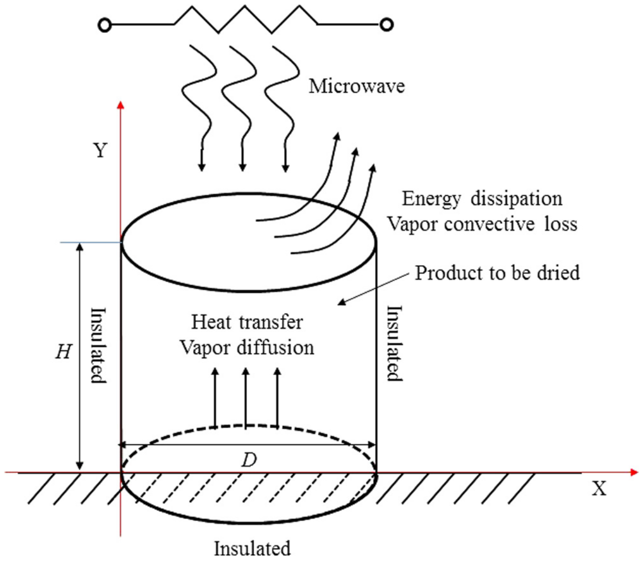

**Fig. 1.** Schematic illustration of microwave heating process.