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# Coupled electromagnetics, multiphase transport and large deformation model for microwave drying

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## HIGHLIGHTS

- Comprehensive description of microwave drying with all relevant physics.
- Electromagnetics, multiphase transport and large deformation solid mechanics are three-way coupled.
- Mechanical deformation critically affects electromagnetics and heat and moisture transport.
- Volume change is primarily due to moisture loss.
- Pressure gradients within the material are responsible for stress development.

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## ABSTRACT

The present work involves development of a fundamentals-based coupled electromagnetics, multiphase transport and large deformation model to understand microwave drying of a hygroscopic porous material. Microwave drying is carried out in a 950 W domestic microwave oven operating at 10% power level. Electric field distribution inside the oven cavity and porous material are obtained by solving Maxwell's equations for electromagnetics. Modes of fluid transport include capillarity, binary diffusion and gas pressure-driven flow. Large deformation, included by treating the solid as hyperelastic, is implemented in a novel way using the Arbitrary-Lagrangian–Eulerian framework for mesh movement. Deformation during microwave drying was found to critically alter material structure that significantly affected microwave absorption, heat and moisture transport within the material. Sensitivity analysis revealed that moisture loss and volumetric shrinkage were unaffected with changes in intrinsic permeability and elastic modulus of the material while stress state within the material was highly sensitive to elastic modulus values.



## 1. Introduction

Microwave (MW) drying is one of the rapid dehydration techniques that has been successfully applied to dry a variety of hygroscopic and porous materials (Kowalski et al., 2010, 2004; Zhang et al., 2006; Sanga et al., 2002; Antti et al., 2000; Garcia and Bueno, 1998; Segerer, 1998; Pakowski and Mujumdar, 1995). Microwave drying of food and agricultural products has been found to result in improved final quality compared with, for example, convective drying (Feng and Tang, 1998; Feng et al., 1999; Drouzas and Schubert, 1996; Torringa et al., 1996). Microwaves heat the material volumetrically causing the temperatures to rise rapidly within the material resulting in internal evaporation of water to vapor. This causes gas pressures to develop within that expel out water from within the core resulting in pressure-driven flow. Consequently, moisture removal is faster and drying times are significantly reduced. However, there are certain limitations of the process, too. Due to microwave absorption, temperatures can rise significantly within the material that may lead to burning (Nijhuis et al., 1998). With high temperatures, evaporation rates become higher leading to extremely large internal pressures that may result in explosion and material destruction from within, ultimately resulting in quality loss (Kowalski et al., 2010; Gulati and Datta, 2015). Moreover, MW drying results in a non-uniform temperature distribution within the material and, in some instances, the edges and corners reach excessively large temperatures resulting in overdrying (Cohen and Yang, 1995; Clark, 1996).

Another important phenomenon that takes place during MW drying is a decrease in volume of the material as moisture is lost during the process (Khraisheh et al., 2004). This significantly affects

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**Nomenclature**

| | |
|---|---|
| $c$ | concentration, kg/m$^{-3}$ |
| $C_p$ | specific heat capacity, J/kg · K |
| $C_g$ | molar density, kmol/m$^3$ |
| $D_{eff,g}$ | vapor diffusivity in air, m$^2$/s |
| $D_{w,cap}$ | capillary diffusivity, m$^2$/s |
| $E$ | elastic modulus, N/m$^2$ |
| $\mathbf{E_{el}}$ | Green–Lagrange strain tensor |
| $\mathbf{E}$ | electric field intensity, V/m |
| $\mathbf{F}$ | deformation tensor |
| $h_t$ | heat transfer coefficient, W/m$^2$ K |
| $h_m$ | mass transfer coefficient, m/s |
| $\mathbf{H}$ | magnetic field intensity, A/m |
| $\dot{I}$ | rate of evaporation, kg/m$^3$ s |
| $\mathbf{I}$ | identity tensor |
| $J$ | Jacobian |
| $k_{in,i}$ | intrinsic permeability, m$^2$ |
| $k_{r,i}$ | relative permeability of component $i$ |
| $K_{evap}$ | evaporation rate constant, 1/s |
| $m$ | overall mass fraction |
| $M$ | moisture content (dry basis), kg water/kg dry solid |
| $M_a$, $M_v$ | molecular weight of air and vapor |
| $\vec{N}$ | unit normal |
| $p$ | pressure, Pa |
| $p_c$ | capillary pressure of water, Pa |
| $Q$ | microwave source term, W/m$^3$ |
| $r$ | radius, $m$ |
| $R$ | universal gas constant, J/kmol K |
| $S_i$ | saturation of a fluid phase, $i$ |
| $\mathbf{S}'$ | Piola–Kirchoff stress tensor, Pa |
| $t$ | time, s |
| $T$ | temperature, °C |
| $\bar{v}$ | velocity, m/s |
| $x_a$, $x_v$ | mole fraction of air and vapor in gas phase |
| $V$ | volume, m$^3$ |
| $x, y, z$ | directions, m |

*Greek symbols*

| | |
|---|---|
| $\rho$ | density, kg/m$^3$ |
| $\lambda$ | latent heat of vaporization, J/kg |
| $\omega_a$, $\omega_v$ | mass fraction of air and vapor |
| $\phi$ | porosity |
| $\mu$ | shear modulus, Pa |
| $\mu_i$ | dynamic viscosity of phase $i$, Pa s |
| $\mu_0$ | permeability of free space, $4\pi \times 10^{-7}$ H/m |
| $\nu$ | Poisson's ratio |
| $\sigma$ | stress, Pa |
| $\varepsilon_0$ | permittivity of free space, $8.854 \times 10^{-12}$ F/m |
| $\varepsilon$ | complex relative permittivity |
| $\varepsilon'$ | dielectric constant |
| $\varepsilon''$ | dielectric loss |
| $\alpha$ | volume fraction |

*Subscripts*

| | |
|---|---|
| *amb* | ambient |
| *a, g, s, v, w* | air, gas, solid, vapor, water |
| *c* | capillary |
| *eff* | effective |
| *el* | elastic |
| *eq* | equilibrium |
| *f* | fracture |
| *G* | ground (stationary observer) |
| *i* | *i*th phase |
| *M* | moisture |
| 0 | at time $t=0$ |
| *surf* | surface |

the material structure and the way it interacts with the microwaves. The ability of a material to absorb microwaves is a strong function of its dielectric properties, i.e., dielectric constant, $\varepsilon'$, and loss factor, $\varepsilon''$. These, in turn, depend upon the moisture content, material structure and volume. A change in both moisture and volume critically affects the capacity of the material to absorb microwaves (Mudgett et al., 1980; Feng et al., 2002) that would manifest itself in drying kinetics of the material during MW drying. Based on the above, one observes a complex interaction between electromagnetics, heat and mass transfer and deformation of the material during microwave drying processes.

Therefore, the main purposes of this article are (1) to develop a fundamentals-based framework consisting of coupled electromagnetics, multiphase and multicomponent transport in porous media, and large deformation phenomena, and (2) use the framework to understand drying of a material inside a microwave cavity. This comprehensive description of the physics of microwave drying by coupling all the relevant phenomena, and in their complete details, will be the novelty of this work. Modeling works in the past have not included all of these physics and their strong coupling—literature modeling studies are detailed in the following paragraph. Using this model, the manuscript sheds light on the effects of some key process parameters of microwave drying on the dried product's final quality.

### 1.1. Previous mathematical models for microwave drying

The microwave drying process involves a complex coupling of three different physics: volumetric heating due to microwaves, heat, mass and momentum transfer of various species (liquid water, water vapor, air) inside the drying material and large deformations of the material. Additionally, for accurate modeling of electromagnetics, all the different physics need to be implemented in the three-dimensional cavity. Available models to study microwave drying processes to date have not considered all these physics. Most of the models are either one or two dimensional heat and mass transfer models involving effective diffusivity for transport and Lambert's law for electromagnetics without considering deformation (Lu et al., 1998; Hansson and Antti, 2003; Durairaj and Basak, 2009; Vongpradubchai and Rattanadecho, 2009). Effective diffusivity formulations combine all modes of transport together and therefore do not describe the process completely. Moreover, 1D or 2D models may not be directly applicable to 3D and would require significant reformulations. Slightly improved versions include 2D transport models in porous media, empirical models for electromagnetics heating (Turner and Perre, 2004; Salagnac et al., 2004) and in some cases including small deformation analysis involving shrinkage coefficients (Kowalski et al., 2004, 2007). Empirical models for electromagnetics do not account for non-uniform heating inside the material and in most cases provide only a qualitative description of the process. Small deformation analysis may be valid in situations where material shrinkage is less than 10%. But, this may not always be true since highly wet materials (e.g., fruits and vegetables) have been found to shrink up to 40% of their volume requiring large