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Microwave drying of spheres: Coupled electromagnetics-multiphase transport modeling with experimentation. Part II: Model validation and simulation results

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ABSTRACT

The coupled electromagnetics and multiphase porous media model, developed in the companion paper, has been applied to the microwave drying of potato spheres. Microwave energy absorption, temperature, pressure and moisture distribution were obtained in 3D samples to gain a comprehensive understanding of the process and address issues such as overheating resulting from microwave focusing. The model was validated against key process parameters and good agreement was found between experimental data and predicted values. The model and experiments demonstrated that the different sized spheres behaved quite differently under similar conditions of drying and general guidelines were obtained for drying sphere-shaped materials. Intermediate sized spheres were found to be more prone to excessive volumetric heating via focusing of microwave energy compared with larger sized spheres. This led to their explosion midway through the drying process; whereas, smaller sized spheres underwent uniform, low temperature drying without any quality loss. Sensitivity analysis showed that the model was highly sensitive to the mass transfer coefficient of the surrounding air inside the microwave oven while intrinsic permeability did not affect moisture loss from the material. This indicated that capillary diffusion is the dominant mode of transport in small sized spheres. Development of this physics-based model would go a long way in making and improving computer-aided design and optimization of microwave drying processes.

1. Introduction

As noted in the companion paper, a fundamentals-based model of microwave drying would provide an indepth understanding of the physics of the process and pave the way for the efficient design, optimization and automation of the microwave drying process. The coupled electromagnetics and multiphase porous media based model presented in the companion paper can provide information about the transient and spatial distribution of microwave energy deposition, temperature, moisture, gas pressure, and evaporation rate during microwave drying that are difficult to obtain from experiments alone. Such information can help understand quality development, for example, understanding the texture of microwave dried materials which is a strong function of temperature and moisture distribution and their histories (Gulati and Datta, 2015). Many of the literature models for microwave drying have treated evaporation as occurring only at the surface.

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Symbols

COV	coefficient of variation
h_m	mass transfer coefficient (m/s)
$k_{in,i}$	intrinsic permeability of component *i* (m^2)
$k_{r,i}$	relative permeability of component *i*
M	moisture content (dry basis) (kg water/kg dry solid)
P	total gas pressure (Pa)
Q	power absorbed (W/m^3)
r	radius (M)
t	time (s)
t	temperature (°C)

Greek symbols

σ	Stress (Pa)

Subscripts

i	inner
o	outer
von	von-Mises
0	time $t = 0$

Such models fail to explain the development of large internal pressures and the role they play in determining the final quality of the product. The model presented here can provide an improved understanding of the drying process and help address issues of overdrying, underdrying, and overheating that adversely affect the final quality of the material (Rakesh et al., 2009). Such a complex physics-based model has many input parameters, not all of which have been measured. Therefore, the mathematical model developed here can help understand the sensitivity of model predictions to various input parameters in order to identify the most critical ones and for which more accurate values may be necessary. Finally, given the flexibility of the modeling framework, the model can be used to simulate certain "what-if" scenarios with the goal of improving drying efficiency. Therefore, the objectives of this research are:

- to solve a fundamentals-based mathematical model developed for a microwave drying process (as shown in the companion paper) and validate the model in terms of point temperature histories, spatial temperature distribution, moisture loss histories and pressure development in different sized spheres for an in depth understanding of the process;
- investigate the factors that cause overheating and non-uniform heating leading to explosion in sphere-shaped materials during their microwave drying; and
- use the computational model to determine model sensitivity to various input parameters and test "what-if" scenarios during the microwave drying process (Section 2.5).

2. Results and discussion

The experimental validation of the mathematical model for three different sample sizes is presented first in terms of key process parameters, such as surface temperature profiles, point temperature histories, moisture loss history and pressure history. This is followed by a comprehensive description of the sample size effect in microwave drying in terms of power absorbed and the distribution of temperature, pressure and moisture. Temperature and moisture uniformity in microwave drying is characterized next. Finally, sensitivity analysis of some of the parameters is carried out to study their effects on the microwave drying process.

2.1. *Experimental validation*

2.1.1. *Moisture loss history*

Fig. 1 shows a comparison between the predicted and experimentally observed moisture content for the different sized spheres. For the 6 cm sample (Fig. 1a), the predicted moisture content matches the experimentally observed values well, with maximum difference being less than 10%. For the 3 cm sample (Fig. 1b), agreement is close until approximately 3 min. During experimental drying, the 3 cm sample exploded creating a hole most likely due to large pressure build-up within the matrix (see Fig. 2). Consequently, the material structure changed drastically, creating additional channels for moisture transport resulting in excessive moisture loss from the material beyond 3 min. Explosion effects are not captured in the modeling framework and therefore there is discrepancy between calculated and measured data beyond 3 min. For the 1.2 cm sample (Fig. 1c), agreement is good up until the first 2 min of drying beyond which there are slight deviations. The lower predicted moisture loss is probably because of shrinkage. The experimental volumetric shrinkage of the material was as high as 25% (data not shown). Therefore, the length scale for moisture transport, i.e., through capillary diffusion and pressure-driven flow, decreased resulting in more moisture loss from the material. Also, for a rigid material, the mixture averaged dielectric property is expected to be lower since the gas phase volume fraction would be higher compared to a shrinking material. As will be discussed in Section 2.2, there is a significant decrease in dielectric properties with an increase in gas porosity that develops due to moisture loss and internal evaporation. With lower dielectric property, the microwave absorption would be lower resulting in lower temperatures and moisture loss from the material. However, incorporating shrinkage effects and associated changes arising due to shrinkage (e.g., heat and moisture fluxes at the moving boundary) is not trivial and would require a complete reformulation of the modeling framework. Nevertheless, the model predicts the transient moisture loss from the different sized spheres reasonably well, showing the effectiveness of the microwave drying model for moisture predictions.

2.1.2. *Temperature histories*

Fig. 3 shows that the predicted and observed temperature histories at the geometric center of the potato spheres are in good agreement. The duration of temperature measurement is different for the 3 cm sample since it exploded after roughly 3 min (8 cycles) into the drying process as noted previously. The experimental values are slightly lower than the computed ones due to (1) a relatively large response time of the temperature probe which takes about 1 s to measure 63% of the actual temperature at a point, and (2) possibly the probe being slightly displaced from its initial location due to large pressure gradients that develop as heating proceeds. The cycling of microwaves is clearly observed from the wavy nature of computed and measured temperatures. For a microwave oven operating at 10% power level, the total cycle time is 22 s during which the magnetron (microwave source in an oven) is ON for 2 s and OFF for the next 20 s.