Modeling of Drying of Cellular Ceramic Structures: Coupled Electromagnetic and Multiphase Porous Media Model

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Introduction

Cellular ceramic substrates are extensively used for pollution control systems in vehicles. The manufacturing process of them can involve microwave drying. In this study, we describe the development of a modeling framework for the microwave drying process of these substrates. The FEM based model consists of two different physics– electromagnetics model for microwave absorption and transport model for heat and moisture transfer in the substrate.

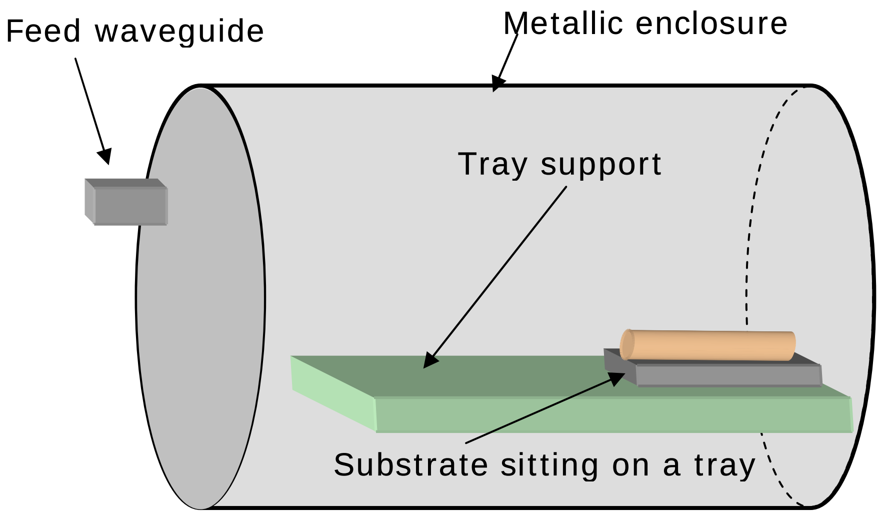

Figure 1: Geometry of the microwave oven

Use of COMSOL Multiphysics

The electromagnetics model for the microwave oven and the substrate is set up using steady state Maxwell's equations. The electromagnetics model provides the heat source term to the transport model. The transport model is based on transient unsaturated flow in multiphase porous media with the substrates considered as porous solids with the pore spaces occupied by liquid water and gas phases. The gas phase further consists of two components: water vapor and air. Local thermal equilibrium assumption means one temperature is shared by all the phases. The transport model is implemented in COMSOL 3.5a using 4 PDEs: 1) Convection-Conduction for temperature, 2) Convection-diffusion for liquid water, 3) Darcy's flow equation for liquid water phase and 4) Stefan-Maxwell's equation for gas phase components.

Ideally, a physics-based model of the drying process needs to capture the EM field in the substrate at every instant so that the heating term for the transport model can be accurately estimated. However, the solution of Maxwell's equations, which govern EM field distribution in the cavity, is computationally intensive and it is unfeasible to solve these equations at every time instant. Therefore, as a compromise, the EM field is updated only after the substrate undergoes significant moisture change. The coupled model is, thus, implemented using the following algorithm:

- In COMSOL GUI, all the equations (with boundary and initial conditions) are set up
- The model is saved as a .m file
- The .m file is edited to:
    - Solve EM code once outside the loop
    - Alternatively solve transport and EM models, each time starting from current solution
- The script is then run using MATLAB

Expected Results

Comparison between predicted and experimentally observed histories of overall drying percentages is shown in Fig 2. It can be seen that overall drying rate is captured very well by the coupled model. Predicted temperature histories at 5 equidistant locations at the central axis of the log are plotted in Fig 3.

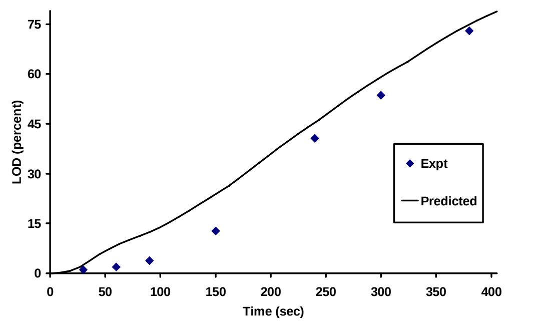

Figure 2: Predicted and observed histories of overall drying percentage of the substrate

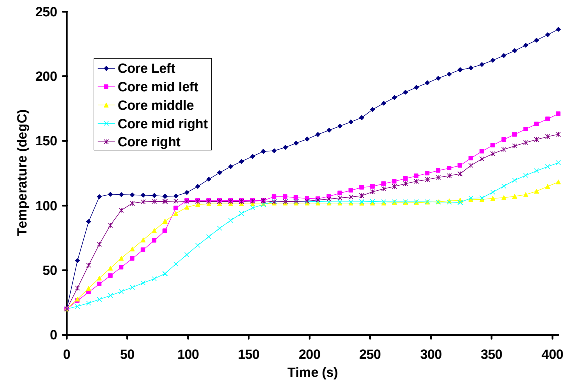

Figure 3: Predicted temperature histories at different locations on the central axis (core) of the substrate

Conclusion

Multiphysics based approach, solving Maxwell's equations for the electromagnetic fields and multiphase porous-media based equations for transport phenomena, has been developed for microwave drying of cellular ceramic substrates. The validity of this approach has been established using experimental results.