Boundary conditions in multiphase, porous media, transport models of thermal processes with rapid evaporationnsert

Amit Halder and Ashim Datta*
Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853
*Corresponding author: 175 Riley Robb Hall, Ithaca, NY-14853

Introduction

In modeling of thermal processing of biological materials with rapid evaporation, it is critical to provide boundary conditions consistent with the phenomena happening at the surface to accurately predict spatial temperature and moisture content for quality and safety assurance. Boundary conditions in a mathematical model are as important as governing equations itself and describe how the heat and mass transfer takes place at the boundary. Until now, the exchange at the boundary has been implemented as a convective heat and mass transfer with constant transfer coefficients. Such a boundary condition is valid for situations where there is no bulk flow and migration of moisture is only due to diffusion. But in thermal processes where rapid evaporation exists, there is significant pressure driven flow inside the porous food and a constant transfer coefficient cannot represent the physics at the surface accurately. A transfer coefficient in such processes is a lumped parameter containing effects of both bulk flow and diffusion and it should change as bulk flow at the surface increases or decreases. To investigate the exchange of heat and moisture at the porous media surface, we solved heat and mass transfer during microwave heating for a conjugate domain including both the porous media food and the outside environment. As a conjugate domain was solved, there was no need to provide separate boundary conditions at the porous media surface. Information about the exchange at the porous media surface was obtained from solving the heat, mass and momentum (Navior-Stokes equation) balances of the surrounding air.

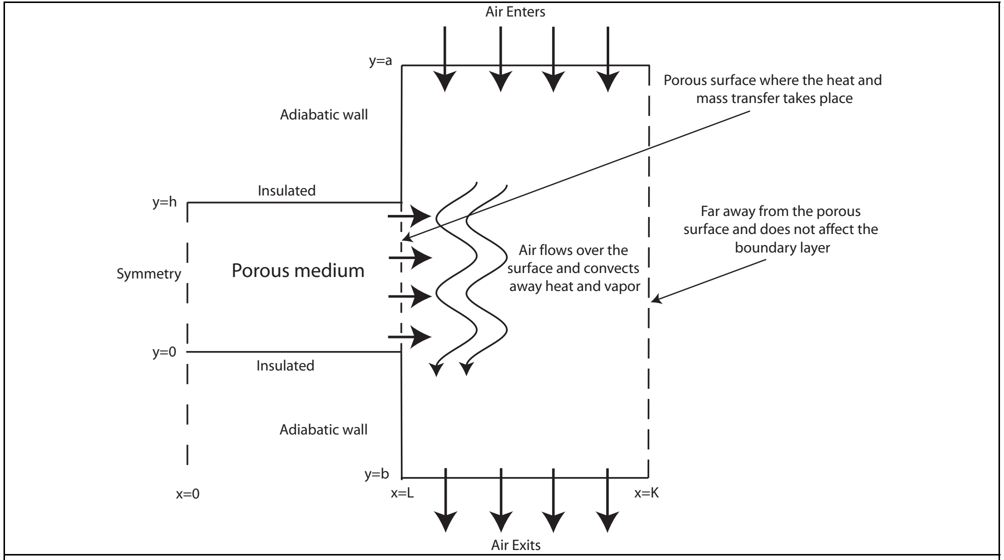


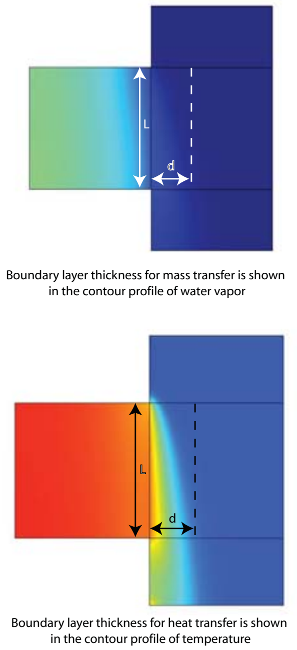
Figure 1: A schematic of the conjugate problem

Use of COMSOL Multiphysics

A multiphase porous media model is developed that describes heat and mass transfer inside a porous material during microwave heating in conjugate with air flow outside the porous material. Mass and energy conservation equations are developed and they include binary diffusion, capillary and convective modes of transport and phase change such as evaporation-condensation. Evaporation is considered distributed throughout the porous domain. Outside the porous media, there is binary diffusion between air and vapor and pressure driven flow and there is no evaporation-condensation. The developed model is solved in COMSOL Multiphysics 3.4 (Chemical Engineering Module). Simulation of microwave heating duration of 10 minutes took approximately 36 hours of CPU time for a timestep size of 0.01 second on a Intel Xeon 3.0 GHz PC with 16GB RAM.

Results

The boundary layer hypothesis is not valid for thermal processing of biological tissues as the thickness of the gradient zone is comparable to the length of the surface (shown in Fig. 2). From the simulation results, the blowing velocity is found to be too small compared to the free stream velocity and therefore has negligible effect on the boundary layer thickness. The mass transfer at the surface is dominated by diffusion and evaporation. The convective mass flux at the surface is negligible compared to the rest two. The mass transfer coefficient, which is a lumped effect of both diffusion and evaporation, increases as the evaporation rate at the surface increases. The heat transfer at the porous surface is dominated by both conduction and convection. The heat transfer coefficient, which is due to conduction only, remains relatively constant throughout the process (shown in Fig. 3).



Boundary layer thickness for mass transfer is shown in the contour profile of water vapor

Boundary layer thickness for heat transfer is shown in the contour profile of temperature

Figure 2. Boundary layer thickness comparable to surface length

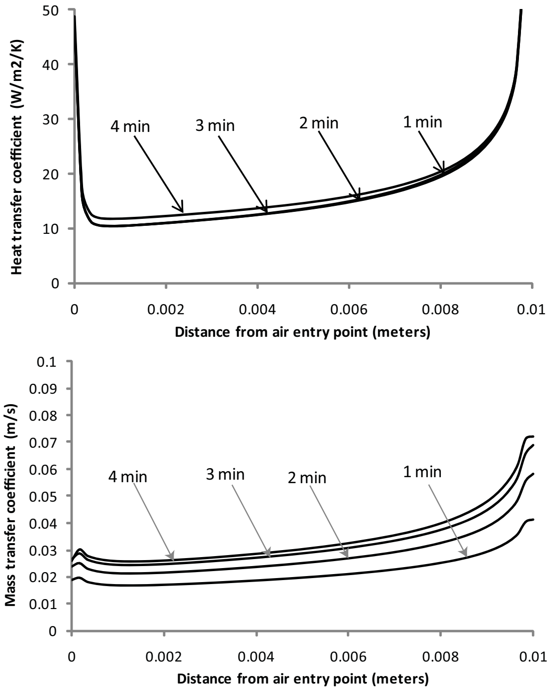


Figure 3. Heat and mass transfer coefficients calculated from conjugate problem

Conclusion

Conjugate problem provides valuable insight into the heat and mass transfer taking place at the surface of the porous media, which is difficult to study through experiments. Based on the results from conjugate simulation, boundary conditions for a non-conjugate problem are formulated, followed by solving the non-conjugate problem. The results match closely thus showing that the developed boundary conditions for non-conjugate problem are in fact predicting what a conjugate problem does. Such boundary conditions are consistent with the physics happening at the porous surface and therefore accurately predict spatial temperature and moisture contents during thermal processes of food.