Multiphase Transport with Large Deformations Undergoing Rubbery-Glassy Phase Transition: Applications to Drying

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Abstract

Drying of biomaterials such as foodstuffs involves mass, momentum and energy transport along with large shrinkage of the porous material, which have significant effects on their final quality. Foodstuffs exhibit non-linearity when undergoing large deformations that affect the transport process in a critical way. Thus, it becomes important to perform a two-way coupling of the multiphase transport and large deformation when modeling drying of foodstuffs. With this objective, a fundamentals-based multiphase porous media model is developed to simulate a drying process and predict certain key quality attributes such as shrinkage and case-hardening. Three phases are considered in the system: solid (skeleton), liquid (water) and gas (water vapor and air). Drying of a cylindrical sample of potato is taken as an example. Modes of liquid water transport include capillary flow and gas pressure driven flow; transport in gas phase is due to diffusion and gas pressure. Evaporation, distributed spatially, is modeled assuming equilibrium between water and water vapor. Equations for the solid mechanics include linear momentum balance and constitutive relationship between the stress and strain assuming potatoes as hyperelastic. A 2-D axisymmetric geometry was constructed in COMSOL Multiphysics 4.2a. Concentration of different species were solved for using the transport of dilute species module (for liquid water) and Maxwell-Stefan Diffusion model (for vapor and air) together with Darcy Law (to calculate Gas Pressure). Temperature of different species was obtained by solving one Heat Transfer equation assuming thermal equilibrium between different phases. Shrinkage and solid displacements were obtained using the Hyperelastic Material model in the Structural Mechanics Module. The model is experimentally validated by comparing temperature, moisture and diameter change histories available from the literature. Complex shrinkage pattern, which is not simply equal to the amount of water lost leads to case-hardening (a thin dried and rigid layer all around), is captured through moisture and state dependent (rubbery/glassy) mechanical and transport properties. Key quality attributes such as crust formation, deviations in shrinkage, porosity development and changes in bulk density, which are related to the glass transition temperature, are predicted. Such a mechanistic approach provides a framework for quality prediction for understanding and improvement of many products and processes beyond simple drying that involve a complex interplay of heat and mass transport and large deformation (shrinkage/swelling).