A Multiphase Porous Medium Transport Model with Distributed Sublimation Front to Simulate Vacuum Freeze Drying

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Abstract

A continuum, porous medium formulation with non-equilibrium sublimation was developed and validated for freeze drying without (Figure 1) and with (Figure 2) uniform microwave volumetric heating (Figure 3). The model was implemented in COMSOL Multiphysics® with Transport of Diluted Species for ice, Heat Transfer in Solids for temperature, and Darcy's Law for pressure. The problem uses multiphysics with each physics being coupled to the other. Excellent agreement was observed with experimental drying curves (Figure 1a and 2a) and spatial temperature data (Figure 1e and 2e). The model incorporates the effect of Knudsen flow at low pressure and low permeability freeze drying. Namely, diffusivity, advection, and thermal conductivity all significantly deviate from their common values presented in literature which are independent of pressure. The distributed, non-equilibrium sublimation demonstrated that the sublimation front is a sharp boundary for high ice saturations (Figure 4) but gradually becomes more distributed as ice saturation decreases. Therefore, models assuming a sharp boundary would be equally as effective at higher ice saturations but, at lower ice saturations, a distributed front approach should be used because the front is no longer localized at one point. The model was very sensitive to porosity, the non-equilibrium constant, volumetric heating, and initial saturation as these four values all strongly control the rate of heat transfer or the energy required for sublimation. Intrinsic permeability had little effect as the pressure is approximately constant, except at the sublimation front. The diffusive transport was the dominating transport mechanism because of the temperature gradient which generated a gas density gradient. Porosity strongly affected the model by increasing the amount of ice and lowering heat flux in dry regions as the gas became an insulator due to being in the Knudsen regime. The non-equilibrium constant significantly affects the computation time by requiring more elements but it also affects the model as values around 10^6 create extremely realistic sublimation fronts through near equilibrium approximation in the dry and frozen region (Figure 4) . The initial saturation changes the thickness of the moving front and shows how lower saturated samples are better modeled with a distributed front rather than the common sharp front. This freeze drying model therefore brings together previous work with non-equilibrium evaporation formulations in porous media and demonstrates that this approach can be extended to sublimation, ultimately creating a general framework for modeling phase change in porous media for application to processing of food and biomaterials.

Reference

Zhao Hiui Wang & Ming Heng Shi, Effects of heating methods on vacuum freeze drying, Drying Technology, 15(5) 1475-1498 (1997)

Zhao Hiui Wang & Ming Heng Shi, Microwave freeze drying characteristics of beef, Drying Technology, 17(3) 434-447 (1999)

Figures used in the abstract

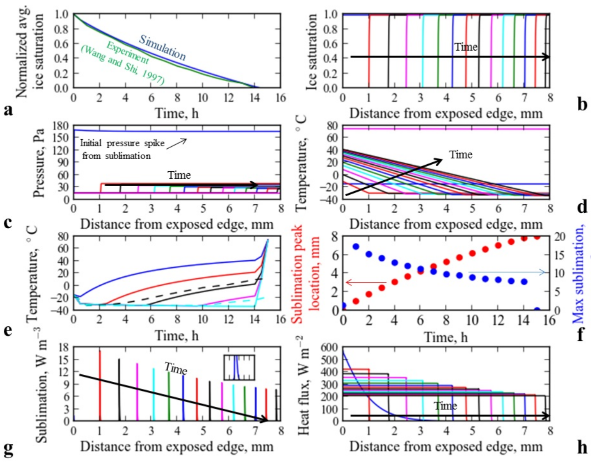

Figure 1: Simulation results for freeze drying without microwave heating.

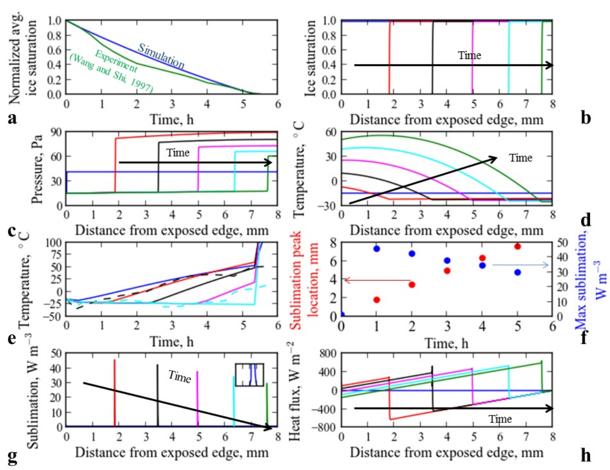

Figure 2: Simulation results for freeze drying with microwave heating.

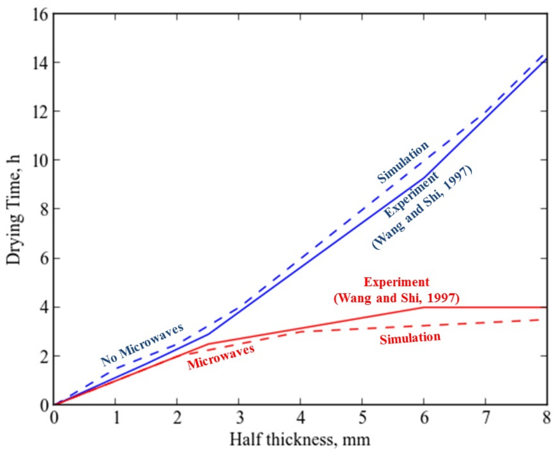

Figure 3: Validation of drying time versus sample thickness.

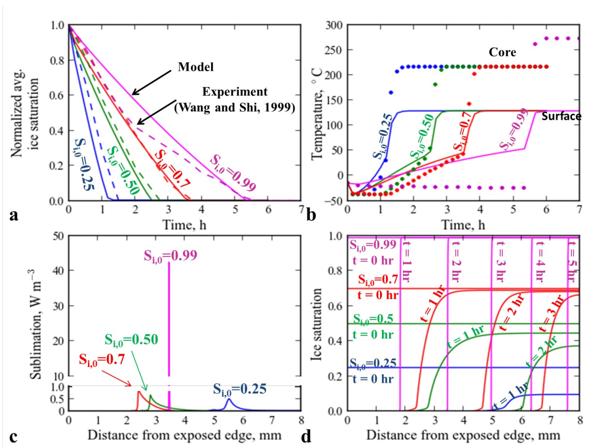

Figure 4: Sensitivity of initial ice fraction saturation.