Simulating Sublimation Front Shapes in Microwave-Assisted Freeze Drying

Investigators: *Isaac Wheeler (Purdue ChemE Ph.D. student), Alina Alexeenko (PI, Purdue), Dimitrios Peroulis (Purdue Electrical and Computer Engineering), Ahmad Darwish (Purdue Electrical and Computer Engineering), Vivek Narsimhan (Purdue ChemE), Drew Strongrich (Purdue LyoHUB), and Petr Kazarin (Purdue AAE, now at IMA Life)*

Microwave-assisted freeze drying is an exciting new method of accelerating the primary drying stage of lyophilization. One advantage of the technology is the ability to bypass the container and heat the frozen product directly, since electromagnetic heating is applied throughout the chamber volume (rather than from a surface, e.g. the top of a shelf). However, as everyday experience with microwave ovens would suggest, glass vials and similar containers may also be heated by the microwave field. This is schematically illustrated in **Figure 1**.

As with conventional lyophilization, models for the heat transfer in MW-assisted lyophilization aid in ensuring product temperatures stay below appropriate limits while accelerating the process. 1D pseudosteady vial-scale models (as typically applied in e.g. LyoPRONTO) are attractive for their simplicity, but assume that there are no temperature gradients in the radial direction (i.e., from vial wall to product center). Experimental measurements indicate that for some microwave-assisted drying conditions, vial walls may be tens of degrees hotter than frozen product, which violates the assumptions necessary for a 1D model. To assess the impact of this effect, a 2D axisymmetric pseudosteady simulation has been implemented in the Julia programming language. This simulation uses the level set method to represent the sublimation front, which allows arbitrary front behavior (including separation from the wall or the vial bottom). Simulations already indicate that for some sets of parameters, the assumption of a planar sublimation front in microwave-assisted lyophilization is reasonable, but not for all process conditions, as in the case shown in **Figure 2** where the front curves noticeably. Future work will establish the delineation in this behavior.

With this simulation method, a variety of other physical effects can also be explored. One is the variation in temperature readings as a function of thermocouple placement in the vial; another is the shape of the sublimation front due to a spatially-varying mass transfer resistance Rp from different pore sizes in the cake (the latter as can be imaged with microCT scanning techniques). The simulation code itself will be published as open source, allowing others to explore these physics in more detail.

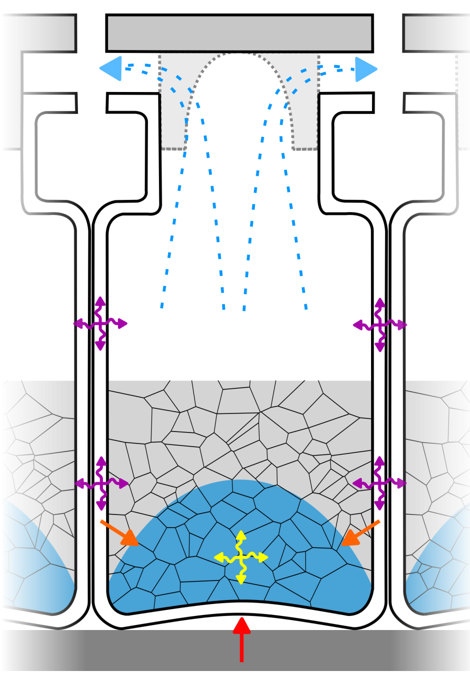

Figure 1: *Schematic of the heat transfer behavior in microwave-assisted lyophilization*

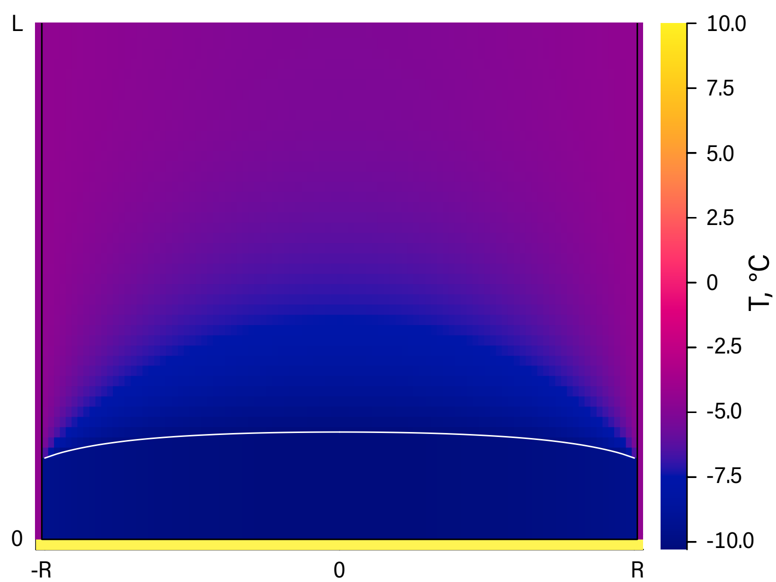

Figure 2: *Simulated temperature throughout the product near the end of primary drying. White line is the sublimation front and the color represents temperature (including shelf and vial wall temperatures), with the ice being the coldest region.*