Design and Validation of a Pressure-based Flow Rate Soft Sensor for Freeze-Drying

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Freeze-drying is a gentle drying process that removes the majority of moisture in a target product without harming the quality of a temperature-sensitive material. It has been used widely for space food and sensitive biological products in pharmaceutical sciences. Freeze-dried food, such as freeze-dried fruits sold in grocery stores, can also be found in people’s daily lives. However, a freeze-drying process takes from a day to up to a week depending on the product attributes, which results in high operating cost. This research focused on developing a process analytical tool (PAT) to enable better drying process design and reduction of processing time.

The study simulates the freeze-dryer process using the computational fluid dynamics (CFD) method, which is a computational tool that uses numerical methods to simulate fluid flows according to specific physical properties and boundary conditions. This research created a new analytical tool, “software sensor” (soft-sensor), to relate measured pressure to instantaneous sublimation rate, the rate of moisture being removed. The modeled fluid flow is then validated with experiments in the actual freeze-drying environment. Results from the verified CFD experiments are recasted into a soft-sensor that takes two pressures at the chamber ($P_{ch}$) and the condenser ($P_{cd}$) as the inputs, as shown in Figure 1, and predicts the instantaneous sublimation rate ($\dot{m}$) as an output of interest. With this capability to predict the sublimation rate, the processing time can be much better estimated and then the design of process parameters can be improved.

There are three main types of fluid flow in typical freeze-dryer ducts: low speed Poiseuille’s flows, high speed choked flow, and flow in between the two regions. Those flow types as well as $\dot{m}$ are dependent on the pressure ($\Delta P = P_{ch} - P_{cd}$). Figure 2, created in this study using CFD, is a contour plot that can be used to predict $\dot{m}$ as a function of the known combination of $P_{cd}$ and $P_{ch}$. Figure 2 had been verified with experimental measurements with satisfactory accuracy, and can be readily used to estimate the freeze-drying sublimation rate based on $P_{cd}$ and $P_{ch}$ data in real time.

Research advisor Tong Zhu writes: “One of the challenges in the process analysis of freeze-drying is the lack of a convenient, inexpensive drying rate sensor. Pasita’s modeling work tactfully processed and reinterpreted existing sensor data, demonstrated accurate predictions against experiments, and created a promising tool for real-time drying rate monitoring in various freeze-drying applications.”
A. LyoStar3® laboratory freeze-dryer and the geometry model and boundary conditions used for CFD modeling.

B. Contour plot for the sublimation rate $m$ as a function of the combination of measured $P_{cd}$ and $P_{ch}$ in the range between 0 to 200 mTorr.