each dryer. A condenser coil surface area as low as 0.6 m^2 was able to accommodate a drying rate of 1 kg/hr. Most of the production dryers had a ratio of condenser to shelf surface areas of just over 1.0, which appears to be sufficient. The cross-sectional areas of the ducts connecting the product and condenser chambers were also analyzed. Of course other aspects of the water vapor flow path can be critical as well—the presence of any obstructions or bends and the length of the connection are also important. At least as far as the cross-sectional area is concerned, a ratio of duct cross-sectional area to shelf area for product of 0.03 should be sufficient.

Shelf Heat Transfer Coefficients

Shelf heat transfer coefficients were calculated per equation (5). In Figure 6 one can see the dramatic range of shelf heat transfer coefficients over the range of shelf fluid temperatures, for a laboratory-scale dryer as well as for a production freeze-dryer. It is not unexpected that there should be such variation with temperature, because the viscosity of the heat transfer fluid will increase with decreasing temperature, reducing the turbulence and therefore the efficiency of heat transfer from the fluid to the inner surfaces of the shelf. The viscosity change will also affect the flow rate of the heat transfer fluid. It was surprising to learn that the flow rate of this critical part of the system was not monitored either on the laboratory-scale unit or on those in production. It is somewhat understandable given that the rate of heat transfer from the fluid to the top of the shelf is rarely a limiting factor. However, in terms of process and product consistency and protection against known failure modes, one would surely find the low cost of a flow meter a small price to pay.

Another surprise was that the heat transfer coefficients for the production freeze-dryer would be so much lower than that for the small dryer. This is another reason to be cautious about transferring a process from a laboratory-scale dryer into one of production size.

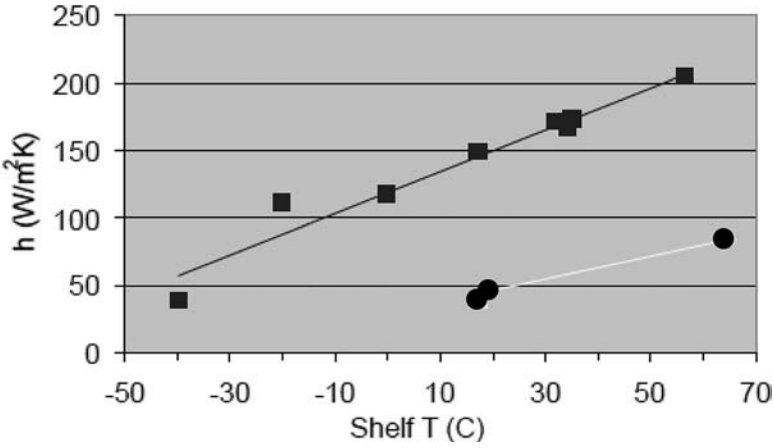

FIGURE 6 Shelf heat transfer coefficients measured during ice slab studies calculated using Equation 5. ■: Laboratory scale dryer. ●: Production scale dryer.