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TECH BRIEF: FREEZE DRYER CONDENSER SURFACE AREA VERSUS SHELF AREA

by Charles D. Dern, P.E.

Proper design of any freeze dryer must take into consideration the sizing of two of its most basic components: heat transfer shelves and the condensing surfaces. Sizing of the shelf area is quite basic in that it must simply be of sufficient area to contain all of the product to be dried in one cycle. The condensing surface area, however, is a different case. In some circles, a strict one to one ratio is adhered to, that is, the condensing area is held equal to the shelf area. However, as shall be shown below, further consideration of the problem shows that adhering to a strict ratio is not the proper method for the sizing of a condenser. These considerations are as follows:

The Tremendous Cryo-Pumping Capability of a Condenser

C.M. Van Atta indicates that the "Pumping Speed" for water vapor of a simple re-entrant trap is 120 CFM per square inch although Van Atta does not provide any factors for temperature and pressure.[1] Steinhertz provides a similar equation that accounts for the temperature and pressure of the system.[2] This formula, when worked through for the typical drying conditions of a pharmaceutical freeze dryer (drying at approximately 200 milliTorr, -10°C vapor temperature and -50°C condenser temperature) yields a capacity of 76 CFM per square inch.

However, condenser size is related here to quantity of water vapor produced (i.e. the rate of sublimation) by the dryer and not directly to the shelf area. Of course, shelf area will determine to some extent the amount of vapor that can be driven off. However, it does not determine the specific amount of vapor that can be driven off per unit area. This is foremost a function of the substance being dried, which in turn determines the temperature and vacuum level of the process.

Consideration of Thickness of Ice and De-sublimation Rate

A more widely used criterion is to provide sufficient condensing area such that by the end of a cycle, the ice is not so thick that it bridges to another plate or structure or, practically, that it unnecessarily extends defrost time. Steinhertz indicates a ratio of 0.2 ft^2 of condenser surface area per pound of ice to be condensed.[3] This ratio works out to approximately 1 inch of ice thickness and in practice would seem to be more of a governing factor for condenser sizing than the cryo-pumping capacity.

A corollary consideration in specifying a maximum ice thickness is the thermal conductivity of ice. Because ice acts as an insulator, the surface of the ice will be warmer than the surface of the actual condenser. The temperature difference between the ice surface and the condenser surface is a function of both the rate of de-sublimation per unit area of condenser and the thickness of the ice. As for the condensing rate, a slower rate will cause a smaller gradient while a faster rate will cause a larger gradient. This is because of the basic nature of heat transfer, which dictates that thermal energy flows in direct proportion to temperature gradient. As for the thickness of ice, the insulating properties of ice are in direct proportion to the ice thickness. Taking into account both factors, the combination of condensing rate and ice thickness cannot be such that the surface temperature of the ice approaches too closely that of the water vapor atmosphere in the condenser.

As for experimental data, Beisswenger measured temperature gradients on the order of 20°C per inch of ice thickness on a fully loaded condenser.[4] This means that the heat transfer medium (refrigerant or heat transfer fluid) must be at least 20°C colder per inch of ice deposited than the required surface temperature. For this instance, if the

[1]Van Atta, C. M., *The Design of High Vacuum Systems, p. 17*

[2]Steinhertz, H.A. *Handbook of High Vacuum Engineering, p. 75*

[3]Ibid. *p. 311*

[4]Beisswenger, Harry L., *Product Improvement Through Advanced Freeze Drying Techniques in* The Bulletin of the Parenteral Drug Association, Mar-Apr. 1969, Vol. 23, No. 2, *p. 98*

condenser has a half-inch of ice, it must 10°C colder while if it had an inch and a half of ice it would need to be 30°C colder. Although, Beisswenger does not supply the sublimation rate that he used, the 20°C temperature gradient is typical of a condenser that is condensing at a rate of 0.2 pounds per square foot per hour.

Note that the Steinhertz ratio and the ice temperature gradient consideration are independent of the required sublimation (shelf) area. This is because at issue is the quantity of ice to be condensed not how much shelf area is required to drive the sublimation process. While it is related to the size of the shelf area, one must also factor in the variable water content of the products to be dried in order to ascertain the required condenser surface area. Therefore, one cannot say that the ratio of condenser to shelf surface area is fixed at 1 to 1 or any other ratio.

Mechanical Considerations

Further considerations would include the total heat transfer capacity of the compressors and the cooling medium. Various compressors have various capacities. Various cooling media (e.g. different refrigerants and/ or heat transfer fluids) also have different heat transfer properties. Both are also factors for which one must account when determining condenser capacity. Both are, again, independent of shelf area.

Example of How Required Condensing Area is Independent Function from the Shelf Area.

From the above it is evident that two systems of significantly differing shelf areas could require the same amount of condenser area. Consider a system with 250 ft^2 of shelf area designed to sublime a 1000 pounds of product that is 63% water by weight. Consider further a second system with 175 ft^2 of shelf area designed to sublime 700 pounds of product that is 90% water by weight. The required ice holding capacity of the two systems are:

System 1 = 1000 lb. x 63 % = 630 pounds of ice

System 2 = 700 lb. x 90 % = 630 pounds of ice

The required ice holding capacities of the condensers are identical!

Using the Steinhertz criterion of 0.2 ft^2 of condenser surface area per pound of ice, the correct condensing area for <u>either</u> system would be 126 ft^2. The condenser to shelf ratio of the first system would be 126/250 or 0.504 while the ratio for the second system would be 126/175 or 0.720. This example demonstrates that as stated above, the ratio is not a constant one.

Experience

SP Industries' experience has proven that systems with condensing area to shelf area ratios of less than 1 to 1 perform quite well. Condensing surface to shelf area in standard Hull machines runs on average from 0.80 to 0.90 to 1. Occasionally, however, Hull has added one or more shelves to its systems to accommodate customer requirements and does so without changing the standard condenser configuration. This has the effect of reducing the ratio even further. Table 1 below is a sample of actual SP production freeze dryers in service today operating with condenser/shelf area ratios well below 1 to 1:

Hull Serial Number	Shelf Area ft2	# Plates	Width in.	Length in	Cond Area ft2	Cond / Shelf Ratio
V32164	320	15	18	47	199	0.62
V32229	144	4	29	47	86	0.59
V32148	300	6	22	59	122	0.41

Table 1: Condenser Area to Shelf Area Ratios in Hull Freeze Dryers

There have been no reported adverse effects on drying capability on any of the above systems or any other similarly configured system.

Conclusion

The above demonstrate that a set ratio of condenser surface to shelf surface of 1 to 1 or of any fixed ratio is insupportable. For the reasons outlined in this brief, correct condenser size must be determined from a multiplicity of factors including product water content, rate of sublimation, required ice holding capacity and overall condenser heat transfer capacity. Shelf surface area is required to calculate some of the aforementioned factors but these factors are not fixed for every product and thus it cannot be said that the ratio of condenser surface area to shelf surface area is fixed.

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