Low Temperature Spray Drying Considerations

Three States of Drying

In convective drying, there are three discernible states in the transition from wet to dry product, *Warmup or Rising Rate, Steady Rate, and Falling Rate*.

Warmup is the first state of convective drying. In this state, the product is at its highest moisture content, and the drying air is relatively dry. At this stage, the surface temperature of the product to be dried is lower than the wet bulb temperature of the drying air. This is the driving mechanism during warmup. The wet bulb temperature of the drying air must be reduced, and the surface temperature of the product must be increased. The drying air therefore transfers heat to the product, and the product transfers moisture to the air. This mechanism will stop when the equilibrium condition is met, i.e., when the surface temperature of the product equals the wet bulb temperature of the drying air.

During *Steady Rate* drying, the surface temperature of the product remains constant, as does the wet bulb temperature of the drying air. There is stable transfer rate of moisture from each droplet core to its surface, and from each droplet surface to the air. The drying chamber is effectively adiabatic during this time. The mechanism for drying in Steady Rate is the difference in partial pressures between water in the air/product boundary layer, and water in the bulk air. (Discussed further below in *Low Temperature Drying Mechanism.*)

Steady Rate continues while the cores of the droplets have sufficient moisture to feed their surfaces at the same rate as their surfaces release moisture to the drying air. However, at some point there will no longer be enough moisture in the core of the droplets to sustain this, the droplet will have effectively transitioned to a wet solid, and mass transfer will begin to slow the process down. This threshold is referred to as the *Critical Moisture Content.* The Critical Moisture Content varies with the size and shape of each droplet, as well as the product itself.

Falling Rate is the last and least efficient state of drying. In this state, there is insufficient moisture near the surface of the product to keep the partial pressure of water in the air/product boundary layer constant. As this partial pressure decreases, the driving force behind drying is reduced. Mass transfer is therefore the bottleneck during this state, as the drying air can remove only the moisture on the surface. Mass transfer is the movement of moisture through the product from the core to the surface, and is governed by two variables; the product itself, and its internal energy.

The product cannot be changed, so the only variable that can be used to increase the driving force for drying is the internal energy of the product. It is relatively difficult to transfer heat via convection during this state, and the drying rate therefore falls continuously until it becomes asymptotic. This is the practical limit for convection drying.

Spray Drying Considerations

This all happens very quickly with spray drying, as the droplet diameter and mass transfer constraints are very small, and the aggregate surface area is very high. However, although the process happens quickly, it nonetheless follows the same rules, and exhibits the same states of drying, rising rate, steady rate, and falling rate.

Steady rate is typically completed in a matter of milliseconds. The commencement of falling rate coincides with the Critical Moisture point of the product, and the formation of a crust on the surface of the droplet, as it transitions to a wet solid. The remaining balance of moisture in the droplet core is removed during falling rate, and is subject to mass transfer constraints. Removal of moisture remaining at the critical point comprises the entire falling rate phase, substantially the balance of product residence time in the drying chamber.

Low Temperature Drying Mechanism

"Equilibrium Moisture Content

> In drying of solids, it is important to distinguish between hygroscopic and non-hygroscopic materials. If a hygroscopic material is maintained in contact with air at constant temperature and humidity until equilibrium is reached, the material will attain a definite moisture content. This moisture is termed the equilibrium moisture content for the specified conditions.
>
> Equilibrium moisture may be absorbed as a surface film or condensed in the fine capillaries of the solid at reduced pressure, and its concentration will vary with the temperature and humidity of the surrounding air.
>
> However, at low temperatures, e.g., 60° F to 120° F, a plot of equilibrium moisture content vs percent relative humidity is essentially independent of temperature. At zero humidity, the equilibrium moisture content of all materials is zero."
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> *(Perry & Chilton, Chemical Engineers' Handbook, Fifth Edition: 20-12, McGraw-Hill)*

The above excerpt illustrates the theory behind drying product at relatively low temperatures. The mechanism for this drying is not the boiling of water, but rather the tendency of two bodies with differing moisture content to reach equilibrium. This is the same mechanism that dries the skin in cold weather. It is driven by the difference between the partial pressures of water vapor in the drying medium (such as air) and on the surface of the moist product.

The surface of the product during Steady Rate drying is always at the wet bulb temperature of the surrounding air (the core of the product will be measurably colder than the surface). At the boundary layer between the product and the air, the temperature of both the product and the surrounding film of air will therefore be the wet bulb temperature. Since the product droplets are wet, the surrounding film of air will be saturated (100% rH).

There is a specific and known partial pressure of water vapor in this film of air which corresponds to 100% rH at the temperature of the boundary layer. The relative humidity of the bulk drying air is not 100%, it is in fact *much* lower, on the order of 2%. This corresponds to a lower partial pressure of water vapor in the bulk air.

This difference in partial pressures causes the water vapor in the boundary layer to migrate into the bulk air. This loss of water vapor is immediately replenished by the surface of the product, drying the product and remoistening the boundary layer air.

This mechanism relates to a drying rate in the following equation: **Drying Rate =** $\mathbf{h_t \bullet A \bullet \Delta_P}$

In this equation, $\mathbf{h_t}$ is the total heat transfer coefficient between the moist product and the convective drying medium (such as air). **A** is the total aggregate surface area of the moist product exposed to the drying medium. **A** is dependent on mean droplet size, droplet concentration in the air, and the size of the drying drying chamber. $\mathbf{\Delta_P}$ is the partial pressure difference discussed earlier.

This equation shows that for a given droplet size and concentration in a drying chamber of a given size, the only variable that directly controls drying rate is the difference in partial pressures ($\mathbf{\Delta_P}$). There are two ways of increasing $\mathbf{\Delta_P}$ and therefore the drying rate; increasing the saturated partial pressure of water vapor at the boundary layer, or decreasing the partial pressure of water vapor in the bulk air.

A conventional dryer is incapable of decreasing the partial pressure of water vapor in the bulk air, because it draws room air, and the partial pressure of water vapor in air does not measurably change with the dry bulb temperature. Instead, a conventional dryer uses heat to increase the surface temperature of the product, which in turn increases the partial pressure of water vapor at the boundary layer.

To a small extent, the heat pump process dryer uses heat in the same manner, however it primarily uses the refrigerant evaporator to substantially decrease the overall moisture content of the bulk air that enters the drying chamber. This combined capability of reducing the partial pressure of water in the bulk air, and increasing the partial pressure of the water in the boundary layer, allows the heat pump dryer to dry faster, at lower drying chamber inlet temperatures, with substantially lower energy consumption. *A conventional dryer cannot do this.*

Low Temperature Drying Practical Considerations

During steady rate, increasing the drying chamber inlet temperature does not materially affect the drying chamber exhaust dew point. However, it does increase the drying chamber exhaust dry bulb temperature. This introduces significant sensible heat into the drying air, that must be removed before moisture condensation can commence.

This sensible heat represents parasitic work that is not used for drying. As the drying chamber inlet dry bulb temperature rises, the sensible heat burden rises concurrently. For a given evaporator size, it is possible for the sensible heat to exceed the evaporator cooling capacity, leaving no cooling capacity for condensation of water. It is substantially more efficient to operate with the lowest practical level of sensible heat.

There is a lower limit to this approach. If the drying chamber exhaust temperature is too low, then condensate may freeze on the evaporator surface. This has substantial compromising effect on air mass flow and heat transfer.

Drying chamber inlet air is preferably as dry as practical, and temperature is just high enough to prevent freezing.

Heat pump closed loop process drying is substantially process agnostic. It may be applied to a wide variety of products including but not limited to milk, whey, baking mixes, baby foods, pharmaceuticals, grain, coffee, tea, and the like.

Low temperature drying uses less energy, and is gentler to the product, materially reducing heat degradation, with no compromise in performance.