Any solids drying operation separates a liquid from a solid material by converting the liquid into a vapor. The liquid is typically water but may be some other solvent depending on the application. For the discussion in this column, we’ll assume the liquid is water.

The driving force for drying is the partial pressure differential between the vapor pressure of the liquid within the solids particles and the vapor pressure of the liquid in the surrounding atmosphere. The surrounding atmosphere is typically air but may also be an inert gas (such as nitrogen), a superheated vapor (steam), or a vacuum. For this column, we’ll assume the surrounding atmosphere to be air.

The energy needed to accomplish the phase change from liquid to vapor is supplied by heat, either through convection, conduction, or radiation. For this column, we’ll limit the discussion to convection and conduction dryers, which are the most common dryer types.

The drying curve
A drying curve, as shown in Figure 1, is a helpful tool for understanding the factors that influence the solids drying process. A drying curve plots

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**Figure 1**

Constant-rate drying zone

Falling-rate drying zone

![Drying curve](image)
a material’s moisture content versus drying time in a batch drying operation. Moisture content (the blue line in the figure) is expressed as percent dry basis, which is pounds of moisture per pound of dry solids. The drying curve in the figure represents a batch drying operation using once-through heated air as the heating medium. The curve also shows the corresponding material temperature versus drying time (the red line in the figure) for the operation.

**Constant-rate drying zone.** The first part of the drying curve represents the constant-rate drying zone. The drying curve in the constant-rate drying zone is a straight line with a negative slope, and the material moisture level steadily decreases. Here, the drying rate is independent of drying time and is controlled only by heat transfer rate—the faster heat transfers to the material, the faster the drying rate. First, the material temperature increases up to the wet-bulb temperature of the drying air, at which point evaporation begins to occur. Then the material remains at the wet-bulb temperature throughout the constant-rate drying zone, and the temperature plot becomes a straight line with zero slope. In the constant-rate drying zone, surface moisture (as well as some internal particle moisture) evaporates into the heated airstream. Evaporation of internal particle moisture will occur as long as the rate of moisture diffusion within the particle is greater than or equal to the rate of moisture evaporation from the particle’s surface. The material temperature remains at the drying air’s wet-bulb temperature until the air becomes saturated and evaporation can no longer occur at that temperature.

**Falling-rate drying zone.** The second part of the drying curve represents the falling-rate drying zone. Proceeding down the drying curve, the material reaches a critical moisture level, below which the particle surfaces are no longer covered with liquid. The material temperature begins to rise and approach the hot air’s dry-bulb temperature, and the slope of the moisture content plot begins to flatten out with drying time. Moisture diffusion becomes the controlling factor for drying. The rising material temperature increases the rate of moisture diffusion within the particles. Particle temperature now plays an important part in the drying rate. Also, particle temperature and residence time determine the final product moisture content in this diffusion-rate-controlled zone.

**Convection drying**

In a convection dryer (also called a direct-contact dryer), heated air comes into direct contact with the material to be dried. The greater the temperature difference between the heated air inlet and the exhaust air outlet, the higher the dryer’s thermal efficiency. This results from the lower flowrate of hot air needed to supply the thermal energy for drying. With the lower airflow rate through the drying circuit, equipment sizing and capital costs will also be reduced.

How high you can go with the heated air inlet temperature will depend on the material being dried. Remember from the drying curve that in the constant-rate drying zone the material will only heat up to the inlet air’s wet-bulb temperature, which is typically much lower than its dry-bulb temperature. This provides some protection from thermal damage to the solids particles in the constant-rate drying zone. However, this doesn’t mean that, when drying a material to a moisture content above the critical moisture level, you can always use any high inlet air temperature. High inlet air temperature can sometimes cause case hardening, where a very high evaporation rate causes the particle surface to develop an impermeable skin that restricts moisture diffusion from the particle’s interior to the surface for evaporation. In such cases, a lower inlet air temperature is required.

As previously mentioned, evaporation in the constant-rate drying zone isn’t just from surface moisture; some internal moisture evaporates as well, depending on the rate at which the moisture diffuses to the particle surface. As a result, the moisture diffusion rate and the length of the diffusion path within the particles can influence convection drying. Particles with smaller diameters or particles such as thin flakes will have shorter diffusion paths for moisture to reach the particle surface and will dry faster than larger-diameter particles. Particle porosity will also affect the drying rate since moisture will diffuse more quickly through porous particles than through dense particles.

When the dryer enters the falling-rate drying zone, moisture diffusion becomes the controlling parameter and is determined by the material temperature and particle size. Small particles have a higher surface-area-to-volume ratio (SA/V) than large particles, which increases heat transfer from the surface to the particle interior. The higher internal particle temperature increases the rate at which moisture diffuses to the particle surface and evaporates.

In the falling-rate drying zone, the drying air's moisture content can also become an important factor. Low-moisture-content (or dehumidified) drying air will have a lower partial pressure, allowing for an increased partial pressure differential to drive evaporation. Moreover, heated, dehumidified air surrounding the particles will reduce the material’s equilibrium moisture level, enabling the dryer to achieve a lower final product moisture content.

A two-stage convection dryer can be a good option for drying applications that require a final product moisture content below the critical moisture level. The first stage can use a higher inlet air temperature to transfer most of the thermal evaporation load with
high thermal efficiency into the constant-rate drying zone. The second stage, using a lower inlet air temperature with dehumidified air, can operate on a reduced evaporation load in the falling-rate, residence-time-controlled zone.

Conduction drying

In a conduction dryer (also called an indirect-contact dryer), the heat source is a heat-transfer fluid such as steam, hot water, or hot oil and is separated from the material to be dried by a metal wall surface. Often, air is used as a sweep mechanism to remove (or sweep) the vaporized moisture from the drying vessel.

Because the amount of sweep air used is relatively low, since the sweep air isn’t used as the heat source, less thermal energy exhausts from the dryer with the evaporated moisture. As a result, thermal efficiency for a conduction dryer is typically quite high — approaching 1,000 to 1,200 Btu per pound of water evaporated. Also, the lower airflow through the dryer allows for smaller ancillary equipment in the drying circuit, which reduces capital costs.

Unlike a convection dryer, in which the evaporating moisture decreases the drying air temperature, a conduction dryer increases (by non-adiabatic indirect heat transfer) the temperatures of both the sweep air and the material up to the evaporating moisture’s boiling point at the system operating pressure. This means that a conduction dryer doesn’t have the wet-bulb temperature protection in the constant-rate drying zone that a convection dryer has.

As a result, material temperature sensitivity is a major factor when considering a conduction dryer. The higher the temperature of the heat transfer fluid, the greater the driving force for heat transfer and the smaller the required dryer size.

But the heat transfer fluid temperature may be limited by the degradation, decomposition, or melting-point temperatures of the material to be dried. Also, since the heat is conducted across a hot metal wall, if the heat transfer fluid temperature is above the material’s sticking point temperature, material fouling can occur on the metal wall surface, which can increase the dryer’s resistance to heat transfer. Finally, if the material’s temperature sensitivity is lower than the liquid’s normal boiling point, a conduction dryer will need to operate under vacuum conditions to effectively evaporate the moisture. If this isn’t an option, you’ll have to use a convection dryer for the application.

John J. Walsh, P.E., is senior consultant at American Drying Consultants (651-263-3697, jjwalshpe@ameridrycon.com). He has a BE in chemical engineering from The City College of New York and has worked in the field of solids thermal processing for more than 40 years. He holds several process and equipment patents and has written numerous technical articles. He’s been an instructor on industrial drying at the Center for Professional Advancement, New Brunswick, NJ, and Amsterdam, The Netherlands.

American Drying Consultants
St. Paul, MN
www.ameridrycon.com

The author will answer your questions in future issues. Direct questions to him at jjwalshpe@ameridrycon.com or to the editor at jbrenny@cspub.com.