# INDUSTRIAL DRYING SYSTEMS

**D**RYING removes water and other liquids from gases, liquids, and solids. The term is most commonly used, however, to describe removing water or solvent from solids by thermal means. **Dehumidification** refers to the drying of a gas, usually by condensation or by absorption with a drying agent (see Chapter 22 of the 2001 *ASHRAE Handbook—Fundamentals*). **Distillation**, particularly **fractional distillation**, is used to dry liquids.

It is cost-effective to separate as much water as possible from a solid using mechanical methods *before* drying using thermal methods. Mechanical methods such as filtration, screening, pressing, centrifuging, or settling require less power and less capital outlay per unit mass of water removed.

This chapter describes industrial drying systems and their advantages, disadvantages, relative energy consumption, and applications.

## MECHANISM OF DRYING

When a solid dries, two processes occur simultaneously: (1) the transfer of heat to evaporate the liquid and (2) the transfer of mass as vapor and internal liquid. Factors governing the rate of each process determine the drying rate.

The principal objective in commercial drying is to supply the required heat efficiently. Heat transfer can occur by convection, conduction, radiation, or a combination of these. Industrial dryers differ in their methods of transferring heat to the solid. In general, heat must flow first to the outer surface of the solid and then into the interior. An exception is drying with high-frequency electrical currents, where heat is generated within the solid, producing a higher temperature at the interior than at the surface and causing heat to flow from inside the solid to the outer surfaces.

## APPLYING HYGROMETRY TO DRYING

In many applications, recirculating the drying medium improves thermal efficiency. The optimum proportion of recycled air balances the lower heat loss associated with more recirculation against the higher drying rate associated with less recirculation.

Because the humidity of drying air is affected by the recycle ratio, the air humidity throughout the dryer must be analyzed to determine whether the predicted moisture pickup of the air is physically attainable. The maximum ability of air to absorb moisture corresponds to the difference between saturation moisture content at wet-bulb (or adiabatic cooling) temperature and moisture content at supply air dew point. The actual moisture pickup of air is determined by heat and mass transfer rates and is always less than the maximum attainable.

ASHRAE psychrometric charts for normal and high temperatures (No. 1 and No. 3) can be used for most drying calculations. The process will not exactly follow the adiabatic cooling lines because some heat is transferred to the material by direct radiation or by conduction from the metal tray or conveyor.

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The preparation of this chapter is assigned to TC 9.2, Industrial Air Conditioning.

**Example 1.** A dryer has a capacity of 41 kg of bone-dry gelatin per hour. Initial moisture content is 228% bone-dry basis, and final moisture content is 32% bone-dry basis. For optimum drying, supply air is at 50°C db and 30°C wb in sufficient quantity that the exhaust air is 40°C db and 29.5°C wb. Makeup air is available at 27°C db and 18.6°C wb.

Find (1) the required amount of makeup and exhaust air and (2) the percentage of recirculated air.

**Solution:** In this example, the humidity in each of the three airstreams is fixed; hence, the recycle ratio is also determined. Refer to ASHRAE Psychrometric Chart No. 1 to obtain the humidity ratio of makeup air and exhaust air. To maintain a steady-state condition in the dryer, water evaporated from the material must be carried away by exhaust air. Therefore, the pickup (the difference in humidity ratio between exhaust air and makeup air) is equal to the rate at which water is evaporated from the material divided by the mass of dry air exhausted per hour.

**Step 1.** From ASHRAE Psychrometric Chart No. 1, the humidity ratios are as follows:

| | Dry bulb, °C | Wet bulb, °C | Humidity ratio, g/kg dry air |
|---|---|---|---|
| Supply air | 50 | 30 | 18.7 |
| Exhaust air | 40 | 29.5 | 22 |
| Makeup air | 27 | 18.6 | 10 |

Moisture pickup is $22 - 10 = 12$ g/kg (dry air). The rate of evaporation in the dryer is

$$41[(228 - 32)/100] = 80.36 \text{ kg/h} = 22.3 \text{ g/s}$$

The dry air required to remove the evaporated water is $22.3/12 = 1.86$ kg/s.

**Step 2.** Assume $x$ = percentage of recirculated air and $(100 - x)$ = percentage of makeup air. Then

Humidity ratio of supply air =
(Humidity ratio of exhaust and recirculated air)$(x/100)$
+ (Humidity ratio of makeup air)$(100 - x)/100$

Hence,

$$18.7 = 22(x/100) + 10(100 - x)/100$$

$x$ = 72.5% recirculated air
$100 - x$ = 27.5% makeup air

## DETERMINING DRYING TIME

The following three methods of finding drying time are listed in order of preference:

- Conduct tests in a laboratory dryer simulating conditions for the commercial machine, or obtain performance data using the commercial machine.
- If the specific material is not available, obtain drying data on similar material by either of the above methods. This is subject to the investigator's experience and judgment.
- Estimate drying time from theoretical equations (see the section on Bibliography). Care should be taken in using the approximate values obtained by this method.

When designing commercial equipment, tests are conducted in a laboratory dryer that simulates commercial operating conditions. Samples used in the laboratory tests should be identical to the material found in the commercial operation. Results from several tested samples should be compared for consistency. Otherwise, test results may not reflect the drying characteristics of the commercial material accurately.

When laboratory testing is impractical, commercial drying data can be based on the equipment manufacturer's experience.

### Commercial Drying Time

When selecting a commercial dryer, the estimated drying time determines what size machine is needed for a given capacity. If the drying time has been derived from laboratory tests, the following should be considered:

- In a laboratory dryer, considerable drying may result from radiation and heat conduction. In a commercial dryer, these factors are usually negligible.
- In a commercial dryer, humidity may be higher than in a laboratory dryer. In drying operations with controlled humidity, this factor can be eliminated by duplicating the commercial humidity condition in the laboratory dryer.
- Operating conditions are not as uniform in a commercial dryer as in a laboratory dryer.
- Because of the small sample used, the test material may not be representative of the commercial material.

Thus, the designer must use experience and judgment to modify the test drying time to suit the commercial conditions.

### Dryer Calculations

To estimate preliminary cost for a commercial dryer, the circulating airflow rate, makeup and exhaust airflow rate, and heat balance must be determined.

**Circulating Air.** The required circulating or supply airflow rate is established by the optimum air velocity relative to the material. This can be obtained from laboratory tests or previous experience, keeping in mind that the air also has an optimum moisture pickup. (See the section on Applying Hygrometry to Drying.)

**Makeup and Exhaust Air.** The makeup and exhaust airflow rate required for steady-state conditions within the dryer is also discussed in the section on Applying Hygrometry to Drying. In a **continuously operating dryer**, the relationship between moisture content of the material and quantity of makeup air is given by

$$G_T(W_2 - W_1) = M(w_1 - w_2) \tag{1}$$

*where*

$G_T$ = dry air supplied as makeup air to the dryer, kg/s
$M$ = stock dried in a continuous dryer, kg/s
$W_1$ = humidity ratio of entering air, kg water vapor per kg dry air
$W_2$ = humidity ratio of leaving air, kg water vapor per kg dry air (In a continuously operating dryer, $W_2$ is constant; in a batch dryer, $W_2$ varies during part of the cycle.)
$w_1$ = dry basis moisture content of entering material, kg of water/kg
$w_2$ = dry basis moisture content of leaving material, kg of water/kg

In **batch dryers**, the drying operation is given as

$$G_T(W_2 - W_1) = (M_1)\frac{dw}{d\theta} \tag{2}$$

*where*

$M_1$ = mass of material charged in a discontinuous dryer, kg per batch
$dw/d\theta$ = instantaneous time rate of evaporation corresponding to $w$

The makeup air quantity is constant and is based on the average evaporation rate. Equation (2) then becomes identical to Equation (1), where $M = M_1/\theta$. Under this condition, humidity in the batch

dryer decreases during the drying cycle, whereas in the continuous dryer, humidity is constant with constant load.

**Heat Balance.** To estimate the fuel requirements of a dryer, a heat balance consisting of the following is needed:

- Radiation and convection losses from the dryer
- Heating of the commercial dry material to the leaving temperature (usually estimated)
- Vaporization of the water being removed from the material (usually considered to take place at the wet-bulb temperature)
- Heating of the vapor from the wet-bulb temperature in the dryer to the exhaust temperature
- Heating of the total water in the material from the entering temperature to the wet-bulb temperature in the dryer
- Heating of the makeup air from its initial temperature to the exhaust temperature

The energy absorbed must be supplied by the fuel. The selection and design of the heating equipment is an essential part of the overall design of the dryer.

**Example 2.** Magnesium hydroxide is dried from 82% to 4% moisture content (wet basis) in a continuous conveyor dryer with a fin-drum feed (see Figure 7). The desired production rate is 0.4 kg/s. The optimum circulating air temperature for drying is 71°C, which is not limited by the existing steam pressure of the dryer.

**Step 1.** Laboratory tests indicate the following:

Specific heats

| | |
|---|---|
| air ($c_a$) | = 1.00 kJ/(kg·K) |
| material ($c_m$) | = 1.25 kJ/(kg·K) |
| water ($c_w$) | = 4.18 kJ/(kg·K) |
| water vapor ($c_v$) | = 1.84 kJ/(kg·K) |

Temperature of material entering dryer = 15°C

Temperature of makeup air

| | |
|---|---|
| dry bulb | = 21°C |
| wet bulb | = 15.5°C |

Temperature of circulating air

| | |
|---|---|
| dry bulb | = 71°C |
| wet bulb | = 38°C |

| | |
|---|---|
| Air velocity through drying bed | = 1.3 m/s |
| Dryer bed loading | = 33.3 kg/m² |
| Test drying time | = 25 min |

**Step 2.** Previous experience indicates that the commercial drying time is 70% greater than the time obtained in the laboratory test. Thus, the commercial drying time is estimated to be $1.7 \times 25 = 42.5$ min.

**Step 3.** The holding capacity of the dryer bed is

$$0.4(42.5 \times 60) = 1020 \text{ kg at 4\% (wet basis)}$$

The required conveyor area is $1020/33.3 = 30.6$ m². Assuming the conveyor is 2.4 m wide, the length of the drying zone is $30.6/2.4 = 12.8$ m.

**Step 4.** The amount of water in the material entering the dryer is

$$0.4[82/(100 + 4)] = 0.315 \text{ kg/s}$$

The amount of water in the material leaving is

$$0.4[4/(100 + 4)] = 0.015 \text{ kg/s}$$

Thus, the moisture removal rate is $0.315 - 0.015 = 0.300$ kg/s.

**Step 5.** The air circulates perpendicular to the perforated plate conveyor, so the air volume is the face velocity times the conveyor area:

$$\text{Air volume} = 1.3 \times 30.6 = 39.8 \text{ m}^3/\text{s}$$

ASHRAE Psychrometric Charts 1 and 3 show these air properties:

Supply air (71°C db, 38°C wb)

| | |
|---|---|
| Humidity ratio | = 29.0 g/kg (dry air) |
| Specific volume | = 1.02 m³/kg (dry air) |

Makeup air (21°C db, 15.5°C wb)

| | |
|---|---|
| Humidity ratio $W_1$ | = 8.7 g/kg (dry air) |

The mass flow rate of dry air is

$$39.8/1.02 = 39.0 \text{ kg/s}$$

**Step 6.** The amount of moisture pickup is

$$0.300/39.0 = 7.7 \text{ g/kg (dry air)}$$

The humidity ratio of the exhaust air is

$$W_2 = 29.0 + 7.7 = 36.7 \text{ g/kg (dry air)}$$

Substitute in Equation (1) and calculate $G_T$ as follows:

$$G_T(36.7 - 8.7)(1 \text{ kg}/1000 \text{ g}) = (0.4/1.04)(82 - 4)/100$$

$$G_T = 10.7 \text{ kg (dry air)/s}$$

Therefore,

| | |
|---|---|
| Makeup air | $= 100 \times 10.7/39.0 = 27.4\%$ |
| Recirculated air | $= 72.6\%$ |

**Step 7.** Heat Balance

| | |
|---|---|
| Sensible heat of material | $= M(t_{m2} - t_{m1})c_m$ |
| | $= (0.4/1.04)(38 - 15)1.25$ |
| | $= 11.1$ kW |
| Sensible heat of water | $= M_{w1}(t_w - t_{m1})c_w$ |
| | $= 0.315(38 - 15)4.18$ |
| | $= 30.2$ kW |
| Latent heat of evaporation | $= M(w_1 - w_2)H$ |
| | $= 0.300 \text{ kg/s} \times 2411 \text{ kJ/(kg·K)}$ |
| | $= 723.3$ kW |
| Sensible heat of vapor | $= M(t_2 - t_w)c_v$ |
| | $= 0.300(71 - 38)1.84$ |
| | $= 18.2$ kW |
| Required heat for material | $= 782.8$ kW |

The temperature drop $(t_2 - t_3)$ through the bed is

$$\frac{\text{Required heat}}{\text{Supplied air, kg/s} \times c_a} = \frac{782.8}{39.0 \times 1.00} = 20 \text{ K}$$

Therefore, the exhaust air temperature is $71 - 20 = 51°C$.

Required heat for makeup air $= G_T(t_3 - t_1)c_a$
$= 10.7(51 - 21)1.00$
$= 321$ kW

The total heat required for material and makeup air is

$$782.8 + 321 = 1100 \text{ kW}$$

Additional heat that must be provided to compensate for radiation and convection losses can be calculated from the known construction of the dryer surfaces.

## DRYING SYSTEM SELECTION

A general procedure for selecting a drying system is as follows:

1. Survey of suitable dryers.
2. Preliminary cost estimates of various types.
   (a) Initial investment
   (b) Operating cost
3. Drying tests conducted in prototype or laboratory units, preferably using the most promising equipment available. Sometimes a pilot plant is justified.
4. Summary of tests evaluating quality of samples of the dried products.

Factors that can overshadow the operating or investment cost include the following:

- Product quality, which should not be sacrificed
- Dusting, solvent, or other product losses
- Space limitation
- Bulk density of the product, which can affect packaging cost

Friedman (1951) and Parker (1963) discuss additional aids to dryer selection.

## TYPES OF DRYING SYSTEMS

### Radiant Infrared Drying

Thermal radiation may be applied by infrared lamps, gas-heated incandescent refractories, steam-heated sources, and, most often, electrically heated surfaces. Infrared heats only near the surface of a material, so it is best used to dry thin sheets.

Using infrared heating to dry webs such as uncoated materials has been relatively unsuccessful because of process control problems. Thermal efficiency can be low; heat transfer depends on the emitter's characteristics and configuration, and on the properties of the material to be dried.

Radiant heating is used for drying ink and other coatings on paper, textile fabrics, paint films, and lacquers. Inks have been specifically formulated for curing with tuned or narrow wavelength infrared radiation.

### Ultraviolet Radiation Drying

Ultraviolet (UV) drying uses electromagnetic radiation. Inks and other coatings based on monomers are cure-dried when exposed to UV radiation. This method has superior properties (Chatterjee and Ramaswamy 1975): the print resists scuff, scratch, acid, alkali, and some solvents. Printing can also be done at higher speeds without damage to the web.

Major barriers to wider acceptance of UV drying include the high capital installation cost and the increased cost of inks. The cost and frequency of replacing UV lamps are greater than for infrared ovens.

Overexposure to radiation and ozone, which is formed by UV radiation's effect on atmospheric oxygen, can cause severe sunburn and possibly blood and eye damage. Safety measures include fitting the lamp housings with screens, shutters, and exhausts.

### Conduction Drying

Drying rolls or drums (Figure 1), flat surfaces, open kettles, and immersion heaters are examples of direct-contact drying. The heating surface must have close contact with the material, and agitation may increase uniform heating or prevent overheating.

Conduction drying is used to manufacture and dry paper products. It (1) does not provide a high drying rate, (2) does not furnish uniform heat and mass transfer conditions, (3) usually results in a poor moisture profile across the web, (4) lacks proper control, (5) is costly to operate and install, and (6) usually creates undesirable working conditions in areas surrounding the machine. Despite these disadvantages, replacing existing systems with other forms of drying is expensive. For example, Joas and Chance (1975) report that RF (dielectric) drying of paper requires approximately four
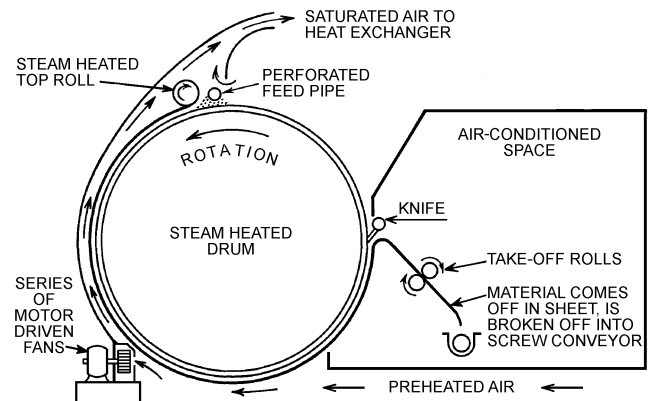


**Fig. 1   Drum Dryer**

times the capital cost, six times the operating (heat) cost, and five times the maintenance cost of steam cylinder conduction drying. However, augmenting conduction drying with dielectric drying sections offsets the high cost of RF drying and may produce savings and increased profits from greater production and higher final moisture content.

Further use of large conduction drying systems depends on reducing heat losses from the dryer, improving heat recovery, and incorporating other drying techniques to maintain quality.

### Dielectric Drying

When wet material is placed in a strong, high-frequency (2 to 100 MHz) electrostatic field, heat is generated within the material. More heat is developed in the wetter areas than in the drier areas, resulting in automatic moisture profile correction. Water is evaporated without unduly heating the substrate. Therefore, in addition to its leveling properties, dielectric drying provides uniform heating throughout the web thickness.

Dielectric drying is controlled by varying field or frequency strength; varying field strength is easier and more effective. Response to this variation is quick, with neither time lag nor thermal lag in heating. The dielectric heater is a sensitive moisture meter.

Several electrode configurations are used. The platen type (Figure 2) is used for drying and baking foundry cores, heating plastic preforms, and drying glue lines in furniture. The rod or stray field types (Figure 3) are used for thin web materials such as paper and textile products. The double-rod types (over and under material) are used for thicker webs or flat stock, such as plywood.

Dielectric drying is popular in the textile industry. Because air is entrained between fibers, convection drying is slow and uneven. Because the yarn is usually transferred to large packages immediately after drying, however, even and correct moisture content can be obtained by dielectric drying. Knitting wool seems to benefit from internal steaming in hanks.

Warping caused by nonuniform drying is a serious problem for plywood and linerboard. Dielectric drying yields warp-free products.

Dielectric drying is not cost-effective for overall paper drying but has advantages when used at the dry end of a conventional steam drum dryer. It corrects moisture profile problems in the web without overdrying. This combination of conventional and dielectric drying is synergistic: the drying effect of the combination is greater than the sum of the two types of drying. This is more pronounced in thicker web materials, accounting for as much as a 16% line speed increase and a corresponding 2% energy input increase.

### Microwave Drying

Microwave drying or heating uses ultrahigh-frequency (900 to 5000 MHz) radiation. It is a form of dielectric heating and is used for heating nonconductors. Because of its high frequency, microwave equipment is capable of generating extreme power densities.

Microwave drying is applied to thin materials in strip form by passing the strip through the gap of a split waveguide. Entry and exit shielding make continuous process applications difficult. Its
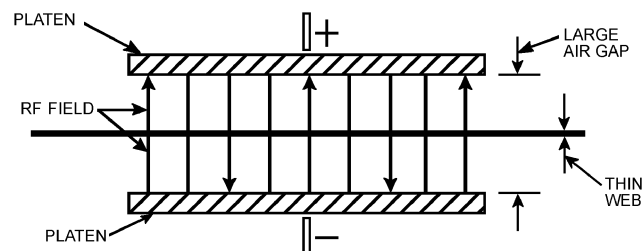
many safety concerns make microwave drying more expensive than dielectric drying. Control is also difficult because microwave drying lacks the self-compensating properties of dielectrics.

### Convection Drying (Direct Dryers)

Some convection drying occurs in almost all dryers. True convection dryers, however, use circulated hot air or other gases as the principal heat source. Each means of mechanically circulating air or gases has its advantages.

**Rotary Dryers.** These cylindrical drums cascade the material being dried through the airstream (Figure 4). The dryers are heated directly or indirectly, and air circulation is parallel or counterflow. A variation is the rotating-louver dryer, which introduces air beneath the flights to provide close contact.

**Cabinet and Compartment Dryers.** These batch dryers range from the heated loft (with only natural convection and usually poor and nonuniform drying) to self-contained units with forced draft and properly designed baffles. Several systems may be evacuated to dry delicate or hygroscopic materials at low temperatures. Material is usually spread in trays to increase the exposed surface. Figure 5 shows a dryer that can dry water-saturated products.

When designing dryers to process products saturated with solvents, special features must be included to prevent explosive gases from forming. Safe operation requires exhausting 100% of the air circulated during the initial drying period or any part of the drying cycle
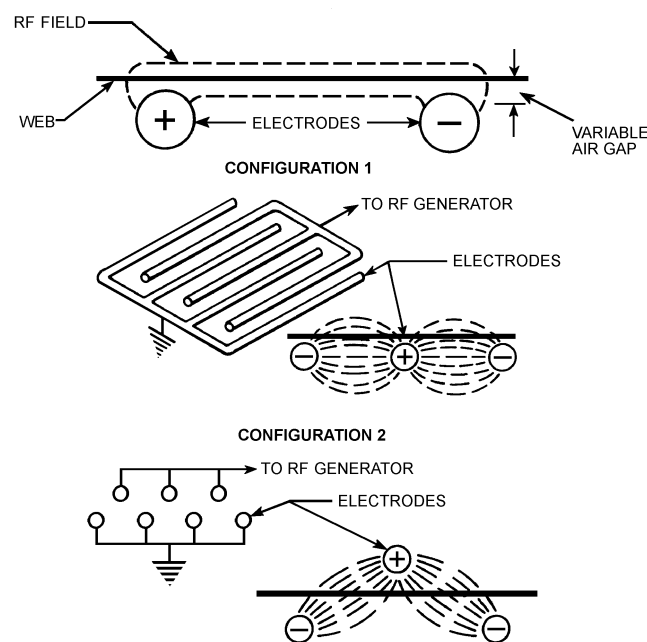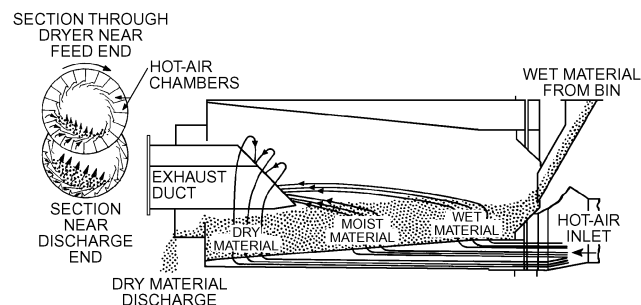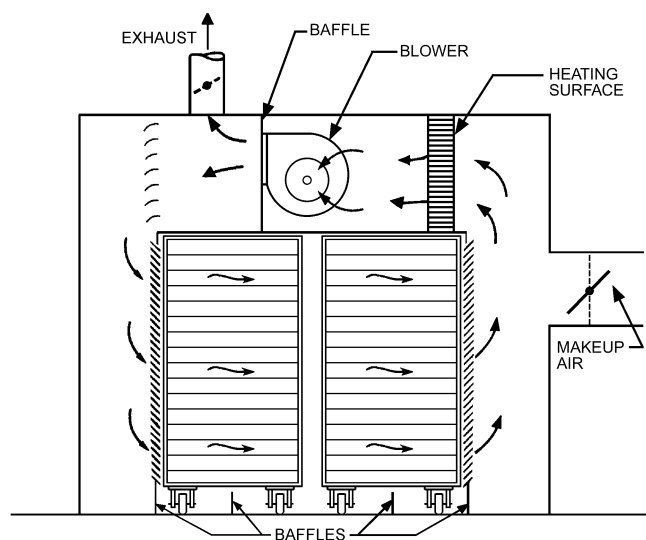


**Fig. 3 Rod-Type Dielectric Dryers**



**Fig. 2 Platen-Type Dielectric Dryer**



**Fig. 4 Cross Section and Longitudinal Section of Rotary Dryer**

**Fig. 5 Compartment Dryer Showing Trucks with Air Circulation**

when solvent is evaporating at a high rate. At the end of the purge cycle, the air is recirculated and heat is gradually applied. To prevent explosions, laboratory dryers can be used to determine the amount of air circulated, cycle lengths, and rate that heat is applied for each product. In the drying cycle, dehumidified air, which is costly, should be recirculated as soon possible. The air *must not* be recirculated when cross-contamination of products is prohibited.

Dryers must have special safety features in case any part of the drying cycle fails. The following are some of the safety design features described in *Industrial Ovens and Driers* (FMEA 1990):

- Each compartment must have separate supply and exhaust fans and an explosion-relief panel.
- The exhaust fan blade tip speed should be 25 m/s for forward-inclined blades, 35 m/s for radial-tip, and 38 m/s for backward-inclined. These speeds produce high static pressures at the fan, ensuring constant exhaust volumes under conditions such as negative pressures in the building or downdrafts in the exhaust stacks.
- Airflow failure switches in both the supply and exhaust ducts must shut off fans and the heating coil and must sound an alarm.
- A high-temperature limit controller in the supply duct must shut off the heat to the heating coil and must sound an alarm.
- An electric interlock on the dryer door must interrupt the drying cycle if the door is opened beyond a set point, such as that wide enough for a person to enter for product inspection.

**Tunnel Dryers.** Tunnel dryers are modified compartment dryers that operate continuously or semicontinuously. Fans circulate heated air or combustion gas is circulated by fans. The material is handled on trays or racks on trucks and moves through the dryer either intermittently or continuously. The airflow may be parallel, counterflow, or a combination obtained by center exhaust (Figure 6). Air may also flow across the tray surface, vertically through the bed, or in any combination of directions. By reheating or recirculating the air in the dryer, high saturation is reached before the air is exhausted, thus reducing the sensible heat loss.

The following problems with tunnel dryers have been experienced and should be considered in future designs:

- Operators may overload product trays to increase output, but this can overtax the system and increase drying time.
- Sometimes air from the drying tunnel is discharged into the production area, increasing the humidity. Air from the drying tunnel should be discharged to the drying system return or outside.
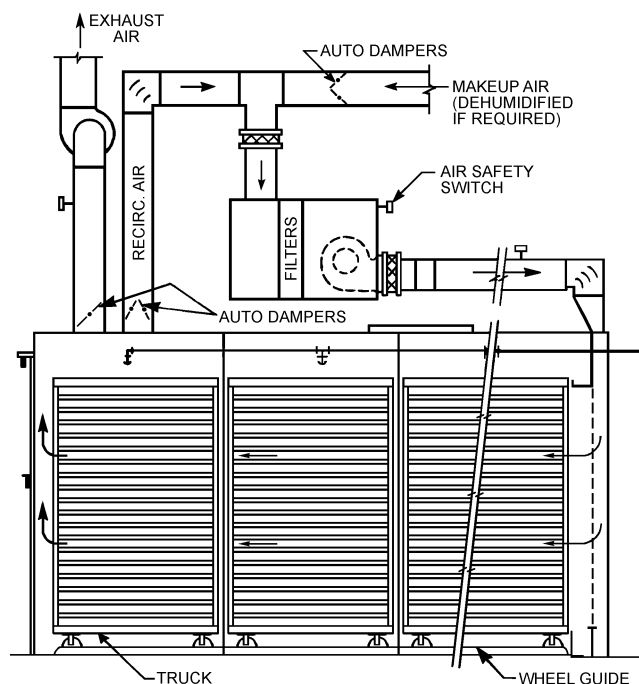


**Fig. 6 Explosionproof Truck Dryer Showing Air Circulation and Safety Features**
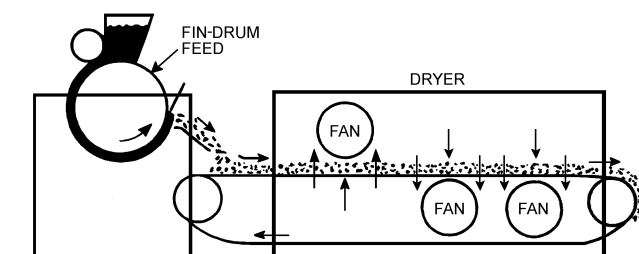


**Fig. 7 Section of Blow-Through Continuous Dryer**

- Overloaded product trays add pressure drop, which decreases flow through the dryer. The control panel should indicate validated flow through the tunnel. High and low flow and high moisture levels should trigger alarms.
- Cycle times can be reduced by designing dryers for cross-flow rather than end-to-end flow.

A variation of the tunnel dryer is the strictly continuous dryer, which has one or more mesh belts that carry the product through it, as shown in Figure 7. Many combinations of temperature, humidity, air direction, and velocity are possible. Hot air leaks at the entrance and exit can be minimized by baffles or inclined ends, with the material entering and leaving from the bottom.

**High-Velocity Dryers.** High-velocity hoods or dryers have been used to supplement conventional cylinder dryers for drying paper. When used with conventional cylinder dryers, web instability and lack of process control result. Where internal diffusion is not the controlling factor in the drying rate, applications such as thin permeable webs offer more promise.

**Spray Dryers.** Spray dryers have been used in producing dried milk, coffee, soaps, and detergents. Because the dried product (in the form of small beads) is uniform and drying time is short (5 to 15 s), this drying method has become more important. When a liquid or slurry is dried, the spray dryer has high production rates.
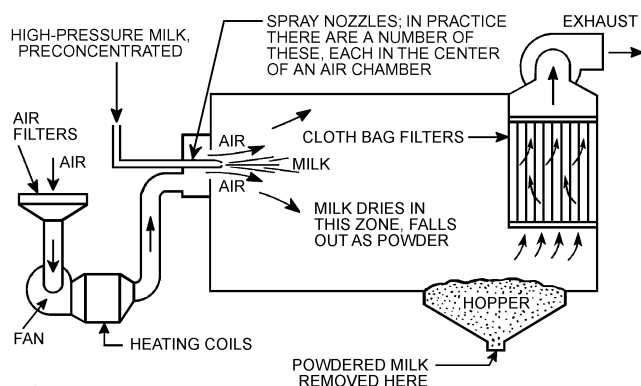
**Fig. 8    Pressure-Spray Rotary Spray Dryer**

Spray drying involves atomizing a liquid feed in a hot-gas drying medium. The spray can be produced by a two-fluid nozzle, a high-pressure nozzle, or a rotating disk. Inlet gas temperatures range from 93 to 760°C, with the high temperatures requiring special construction materials. Because thermal efficiency increases with the inlet gas temperature, high inlet temperatures are desirable. Even heat-sensitive products can be dried at higher temperatures because of the short drying time. Hot gas flow may be either concurrent or countercurrent to the falling droplets. Dried particles settle out by gravity. Fine material in the exhaust air is collected in cyclone separators or bag filters. Figure 8 shows a typical spray drying system.

The physical properties of the dried product (such as particle size, bulk density, and dustiness) are affected by atomization characteristics and the temperature and direction of flow of the drying gas. The product's final moisture content is controlled by the humidity and temperature of the exhaust gas stream.

Currently, pilot-plant or full-scale production operating data are required for design purposes. The drying chamber design is determined by the nozzle's spray characteristics and heat and mass transfer rates. There are empirical expressions that approximate mean particle diameter, drying time, chamber volume, and inlet and outlet gas temperatures.

### Freeze Drying

Freeze drying has been applied to pharmaceuticals, serums, bacterial and viral cultures, vaccines, fruit juices, vegetables, coffee and tea extracts, seafoods, meats, and milk.

The material is frozen, then placed in a high-vacuum chamber connected to a low-temperature condenser or chemical desiccant. Heat is slowly applied to the frozen material by conduction or infrared radiation, allowing the volatile constituent, usually water, to sublime and condense or be absorbed by the desiccant. Most freeze-drying operations occur between −10 and −40°C under minimal pressure. Although this process is expensive and slow, it has advantages for heat-sensitive materials (see Chapter 15 of the 2002 *ASHRAE Handbook—Refrigeration*).

### Vacuum Drying

Vacuum drying takes advantage of the decrease in the boiling point of water that occurs as the pressure is lowered. Vacuum drying of paper has been partially investigated. Serious complications arise if the paper breaks, and massive sections must be removed. Vacuum drying is used successfully for pulp drying, where lower speeds and higher masses make breakage relatively infrequent.

### Fluidized-Bed Drying

A fluidized-bed system contains solid particles through which a gas flows with a velocity higher than the incipient fluidizing veloc-

ity but lower than the entrainment velocity. Heat transfer between the individual particles and the drying air is efficient because there is close contact between powdery or granular material and the fluidizing gas. This contact makes it possible to dry sensitive materials without danger of large temperature differences.

The dried material is free-flowing and, unlike that from convection dryers, is not encrusted on trays or other heat-exchanging surfaces. Automatic charging and discharging are possible, but the greatest advantage is reduced process time. Only simple controls are important: over (1) fluidizing air or gas temperatures and (2) the drying time of the material.

All fluidized-bed dryers should have explosion-relief flaps. Both the pressure and flames of an explosion are dangerous. When toxic materials are used, uncontrolled venting to the atmosphere is prohibited. Explosion suppression systems, such as pressure-actuated ammonium-phosphate extinguishers, have been used instead of relief venting. An inert dryer atmosphere is preferable to suppression systems because it prevents explosive mixtures from forming.

When organic and inflammable solvents are used in the fluidized-bed system, the closed system offers advantages other than explosion protection. A portion of the fluidizing gas is continuously run through a condenser, which strips the solvent vapors and greatly reduces air pollution problems, thus making solvent recovery convenient.

Materials dried in fluidized-bed installations include coal, limestone, cement rock, shales, foundry sand, phosphate rock, plastics, medicinal tablets, and foodstuffs. Leva (1959) and Othmer (1956) discuss the theory and methods of fluidization of solids. Clark (1967) and Vanecek et al. (1966) developed design equations and cost estimates.

### Agitated-Bed Drying

Uniform drying is ensured by periodically or continually agitating a bed of preformed solids with a vibrating tray, a conveyor, or a vibrating mechanically operated rake, or, in some cases, by partial fluidization of the bed on a perforated tray or conveyor through which recycled drying air is directed. Drying and toasting cereals is an important application.

### Drying in Superheated Vapor Atmospheres

When drying solids with air or another gas, the vaporized solvent (water or organic liquid) must diffuse through a stagnant gas film to reach the bulk gas stream. Because this film is the main resistance to mass transfer, the drying rate depends on the solvent vapor diffusion rate. If the gas is replaced by solvent vapor, resistance to mass transfer in the vapor phase is eliminated, and the drying rate depends only on the heat transfer rate. Drying rates in solvent vapor, such as superheated steam, are greater than those in air for equal temperatures and mass flow of the drying media.

This method also has higher thermal efficiency, easier solvent recovery, and a lower tendency to overdry, and it eliminates oxidation or other chemical reactions that occur when air is present. In drying cloth, superheated steam reduces the migration tendency of resins and dyes. Superheated vapor drying cannot be applied to heat-sensitive materials because of the high temperatures.

Commercial drying equipment with recycled solvent vapor as the drying medium is available. Installations have been built to dry textile sheeting and organic chemicals.

### Flash Drying

Finely divided solid particles that are dispersed in a hot gas stream can be dried by flash drying, which is rapid and uniform. Commercial applications include drying pigments, synthetic resins, food products, hydrated compounds, gypsum, clays, and wood pulp.

## Constant-Moisture Solvent Drying

In some cases it is desirable to dry organic solvents from a substance without changing moisture content. This is particularly true in drying pharmaceutical products, which are commonly bound with solvents such as isopropyl alcohol (IPA) or acetone. Loss of moisture content can affect the stability of some pharmaceutical compounds, which therefore must be liberated of bound solvents without changing the relative humidity. Most pharmaceutical facilities producing oral solid dosage (OSD) presentations manufacture in spaces that range from 30 to 45% rh. To maintain this level of humidity at the temperatures needed to liberate the organic solvents at the required rate, an oven must be fitted with an adequately sized humidifier. Figure 9 shows the compartment dryer from Figure 5 adapted for constant-moisture drying.

It is vital to size the preheat coil to the humidifier to allow enough "room" to provide the humidification level required. The amount of preheat is usually enough to provide makeup air to the oven at 90% rh. This allows the oven heaters to control drying temperature at the more common oven humidity levels of 30 to 45% rh. If electric heat is used, the ability to constantly vary the capacity of the heaters must be provided; silicon-controlled rectifiers (SCRs) are commonly used.

Additional insulation on the outside of the oven and the ductwork from the humidifier section onward should also be considered. Care must be taken to ensure that unwanted condensation does not form inside the oven. Dripping moisture can sometimes ruin the product, causing a substantial economic loss. If the product is pharmaceutical, then the humidifier makeup water source should be deionized or produced to comply with U.S. Pharmacopoeia XXIII, Supplement 8 (effective May 1998).
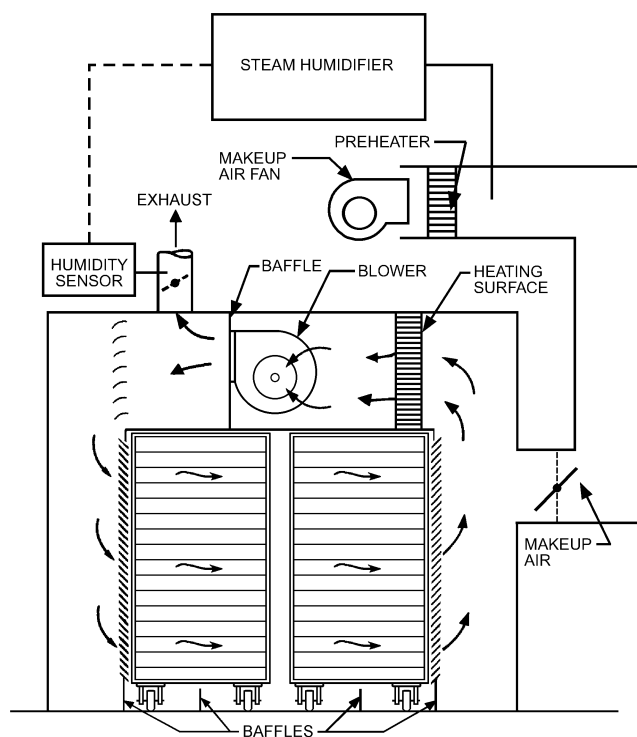


**Fig. 9   Humidified Cross-Flow Tray Dryer**

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