content. It should be noted, however, that it is more difficult to operate an indirect dryer in a continuous mode under vacuum.

Another noted advantage of indirect dryers is the higher product quality attainable. This is because the flows into and out of the dryer are relatively small when operating in a batch mode and indirect dryer is practically a closed system. As a result, this type of dryer is suitable for situations where process conditions are required.

Accompanying the above advantages of indirect dryers are several limitations such as their limited ability to enhance the drying rates due to availability of the heat transfer areas, especially for large-scale equipment. Indirect dryers also possess lower maximum drying temperature and throughput when compared to direct dryers. Many types of indirect dryers can only be operated in batch mode; hence they have lower production capabilities than direct dryers. In addition, indirect dryers have typically higher capital costs than equivalent direct dryers due to the need for heat exchange surfaces and in contact with the wet material being dried. In some cases, the drying chamber is equipped with an agitator. Condensing steam (most popular heating medium), hot water, combustion gases, molten salts, or electricity (less popular due to high cost involved) can be used to heat the jacket, which in turn transfers heat to the drying surface (by conduction or, in some cases, conduction and radiation). The heating medium and the product to be dried are separated by a drying surface as shown schematically in Figure 6.1. The agitator or the rotation of the drying chamber

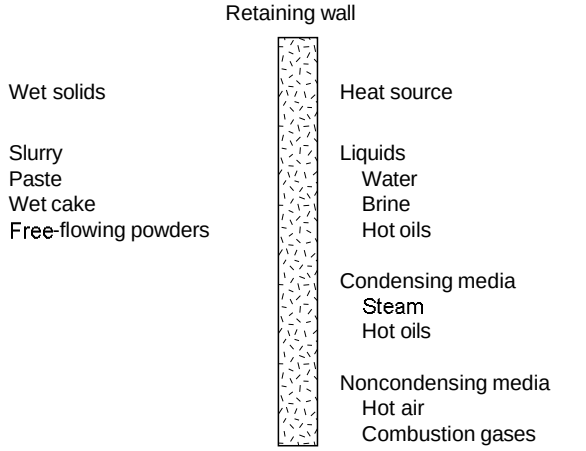


FIGURE 6.1 Schematic diagram of a typical indirect dryer; material to be dried is separated from heat source by a conducting wall.

6.2 CLASSIFICATION AND SELECTION CRITERIA

The choice of an indirect dryer is generally determined by the material to be dried. Some common indirect dryers and their applications to various feedstock forms are listed in Table 6.1. It should be noted that some additional operations, e.g., product backmixing, could be employed to change the material characteristics, which permits the use of additional dryer types than those listed here. Table 6.2 lists the types of indirect dryers that are suitable for various requirements, both in terms of the operating conditions and the types of feedstock.

Product quality is always of great concern when selecting the type of dryer to be used. Controlling the level of product volatiles is also, in some cases, important. To satisfy these demands the selected dryer should provide the optimum conditions for the time–temperature exposure of the drying material (Kimball, 2001). An indirect dryer that uses high heat-source temperature should be operated in such a way that the residence time of the drying material within it is

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TABLE 6.1
Indirect Dryer Selection Based on Feedstock Form

Nature of Feed	Liquids			Cakes				Free-Flowing Solids			Formed-Shaped Solids
	Solutions	Slurry	Pastes	Centrifuge	Filter	Powder	Granules	Fragile		Fiber	
								Crystal	Pellet		
Dryer types											
Thin-film contact											
Cone, batch											
Drum											
Steam-jacket rotary											
Tray, batch											
Tray, continuous											

Source: Adapted from Kimball, G., *Chemical Engineering*, May 2001, pp. 74–81.

minimized; the dryer that operates at lower temperature can be operated with a longer residence time for material within it. In applications that require low product volatile levels a dryer with long residence-time capabilities and gas counterflow may be required. Table 6.3 lists the solids exposure time of some selected indirect dryers. It can be seen that a wide range of residence time, i.e., from a few seconds to few hours, can be accommodated by using different types of indirect dryers.

The guidelines for the selection of some specific dryers, e.g., agitated vacuum dryers, are available in the literature (Fuller, 1999).

6.3 TYPES OF INDIRECT DRYERS

6.3.1 BATCH TRAY DRYERS

In this basic type of indirect dryers the material to be dried is placed in pans or trays on the hollow shelves,

TABLE 6.2
Indirect Dryer Selection Criteria

Dryer Type	Plate	Drum	Tumbling	Vibrating	Conical	Thin Film	Paddle	Mixer-Kneader
Requirement								
Continuous								
Discontinuous								
Vacuum			þ					
Large surface area/volume	þ				þ	þ	þ	
High specific capacity	þ				þ		þ	
Materials								
Friable						þ		
Fluid								
Viscous/pasty								
Crusty							þ	
Processing								
Mechanical								
Thermal						þ	þ	þ
	þ			þ	þ			

, not suitable; , sometimes suitable; þ, good; , ideal.

Source: Thurner, F., *Chemical Engineering*, October 1993, pp. 20–22.

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TABLE 6.3
Solids Exposure Time of Some Indirect Dryers

Typical Residence Time of Dryer	0–10 s	10–30 s	5–10 min	10–60 min	1–6 h
Thin-film contact					
Cone, batch					
Drum					
Steam-jacket rotary					
Tray, batch					
Tray, continuous					

Source: Adapted from Kimball, G., *Chemical Engineering*, May 2001, pp. 74 – 81.

which are heated by the heating medium, which can range from high-pressure steam for moderate-to-high temperature operation to subatmospheric steam for low-temperature operation to hot oil, or even by an electric heater in the case of smaller units. The trays are generally metal to ensure good heat transfer between the trays and the shelves. The number of shelves ranges from 1 to more than 20 shelves in a large unit.

For heat-sensitive materials drying can take place at low temperature with the application of vacuum to reduce the boiling point of the liquid to be removed, which can be toxic or valuable solvents that must be recovered. Vacuum is applied to the drying chamber and vapor is removed through an exhaust pipe connected to the chamber; this line is also connected to a condenser where vapor is condensed and, possibly, recovered. The noncondensable gas exits through the vacuum source, which can be a vacuum pump or a steam-jet ejector.

In a standard design all shelves are contained in a single drying chamber, whereas in an alternative design the dryer may be divided into a number of separate chambers to allow more flexible operation as individual trays can be loaded or unloaded separately. Typically, each tray may be loaded up to a depth of about 40 mm giving a loading of approximately 40 kg of wet material/m^2 of tray area (Oakley, 1997).

This type of dryers, along with the use of vacuum, is used extensively for drying heat-sensitive or easily oxidized materials. They are particularly well suited for materials, which require gentle handling and where material loss must be minimized. Hygroscopic materials may also be dried completely at temperatures lower than the maximum permissible temperatures of those materials. The major disadvantages of this type of dryers are the high labor cost involved during the loading and unloading of the drying materials and the low capacities of the units.

6.3.2 Indirect-Contact Rotary Dryers

The most common type of indirect-contact rotary dryers is the steam-tube dryer (Figure 6.2). This type of dryer basically consists of a cylindrical shell, typically inclined slightly (1° to 5°) to the horizontal to

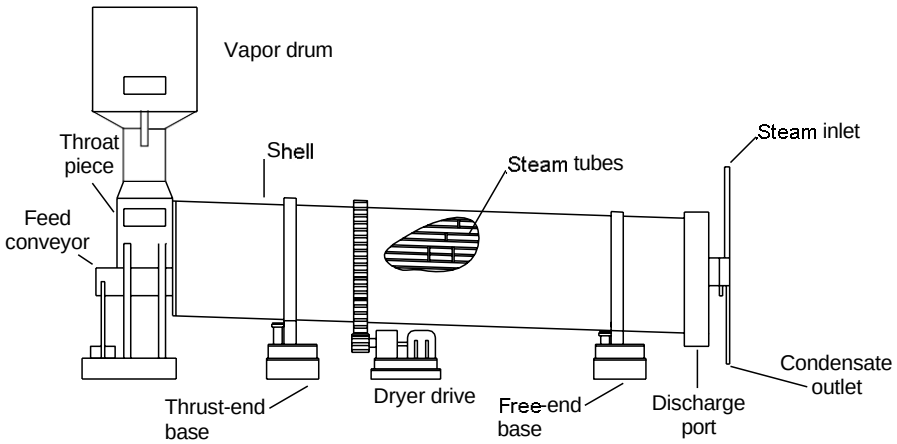


FIGURE 6.2 Indirect-contact rotary dryer.

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facilitate the transportation of the wet feedstock through its body, and in which a number of steam- heated tubes are placed symmetrically (in one, two, or three concentric rows) around its perimeter and rotate with it. The length to diameter ratio of the rotating shell can vary from 4:1 to 10:1. Steam-heated tubes may either be simple pipes with condensate draining by gravity into the discharge manifold or bayonet- type; typical steam pressure used may be in the range of 4 – 10 bar (van' t Land, 1991). When handling sticky materials one row of tubes is preferred. Lifting flights are usually inserted behind the tubes to aid agitation. Typically, indirect rotary dryers would be used when direct-contact rotary dryers are not suitable either because direct contact with hot gases is not permis- sible for product quality reasons or because of the presence of fine particles, which can be entrained along with the drying gas flows (Oakley, 1997).

Wet feed enters the dryer at the upper end of the shell and tumbles around the steam tubes and dries. Gentle airflow (generally countercurrent to solids flow) is normally applied to the drying chamber to carry away the evaporated moisture. This type of dryer is used for continuous drying or heating of granular or powdery solids, which cannot be exposed to ordinary atmospheric or combustion gases. It is especially suitable for fine dusty particles as only low gas velocities are needed to purge the drying chamber.

Comparing to their direct-contact counterparts indirect-contact dryers possess some advantages such as the reduced deterioration of the drying material due to an excessive exposure of the material to the high-temperature drying medium. In addition, adsorption of such toxic substances in the drying medium (in the case where direct combustion gases are used) as NO_x is eliminated.

The thermal efficiency of steam-tube dryers is in the range of 70 – 90%, if well insulated. This number does not allow for boiler efficiency, so it cannot be directly compared with that of direct-heat units, however. Heat transfer coefficients in steam-tube dryers may range from 30 to 85 W/(m^2 K) and these values increase with increasing steam tempera- ture due to an increased effect of radiation. The heat flux of these dryers, carrying saturated steam at 140 – 170°C, may range from 6300 W/m^2 for difficult-to-dry and organic products to between 1900 and 3800 W/m^2 for fine inorganic materials. Typical performance data of steam-tube dryers on some selected applications are shown in Table 6.4 (Moyers and Baldwin, 1997).

Mathematical models that specifically enable prediction of the moisture content and temperature profiles of the material undergoing drying in an indirect-contact steam-tube dryer are available in the literature (e.g., Shene and Bravo, 1998; Canales et al., 2001).

TABLE 6.4
Indirect Steam-Tube Dryer Performance Data

	Type 1	Type 2	Type 3
Type of materials processed	High-moisture organic, distillers' grains, citrus pulp	Pigment filter cakes, precipitated chalk	Finely divided inorganic solids, floatation concentrates
Feed description	Wet feed is granular solid and damp but not sticky and dries to granular solid	Wet feed is pasty and dries to hard pellets	Wet feed is crumbly and friable and dries to powdery product of very few lumps
Moisture content of wet feed (%, d.b.)	223	100	54
Moisture content of product (%, d.b.)	11	0.15	0.5
Normal temperature of wet feed (K)	310 – 320	280 – 290	280 – 290
Normal temperature of product (K)	350 – 355	380 – 410	365 – 375
Evaporation per kg of product (kg)	2	1	0.53
Heat load per kg of product (kJ)	4950	2620	1375
Heating surface required per kg of product (m^2)	0.34	0.4	0.072
Steam (at 860 kPa gauge) consumption per kg of product (kg)	3.33	1.72	0.85

Source: Adapted from Moyers C.G., Baldwin, G.W., in R.H. Perry and D.W. Green, eds. *Perry's Chemical Engineers' Handbook*, 7th ed., McGraw-Hill, New York, 1997, pp. 12-1 – 12-90.

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6.3.3 Rotating Batch Vacuum Dryers

The rotating (or double cone) batch vacuum dryer is essentially a rotating vessel containing materials to be dried. This type of dryers is widely used to dry such materials as free-flowing powders, granules, and crystals. Due to the gentle tumbling motion this type of dryers, however, is not suitable for processing sticky materials, which may stick to the dryer walls or form lumps. Vacuum is used in conjunction with drying when low solid temperatures must be maintained due to heat-sensitive nature of the products or to avoid oxidation or fire or explosion.

Rotating batch vacuum dryers (Figure 6.3) consist of a heated vacuum chamber, which rotates about a horizontal axis. Wet material is loaded through the charge opening and the vessel is closed and evacuated down to the desired operating pressure. Heat for drying is supplied by a surrounding heating jacket. During the drying cycle the vessel rotates and imparts a tumbling motion to the drying material, aiding heat transfer, mixing, and vapor release. The speed of rotation may vary from 5 rpm for a large unit to 30 rpm for a smaller unit. The temperature of the heating jacket may be varied through the drying cycle; it is also common to replace the heating medium by cooling water in the final stage of drying to cooldown the product.

The major disadvantages of this type of dryers are the limited heat transfer areas, especially in larger units. One possible solution to this problem is the addition of internal heating panels; however, this alternative is prone to fouling. The stickiness problem can be alleviated by rotating the vessel slowly or intermittently when the drying material is at high moisture content. However, truly sticky materials may not still be processed in this type of dryers.

The overall heat transfer coefficients of this type of dryer, which may vary near 35 W/(m^2 K), depend

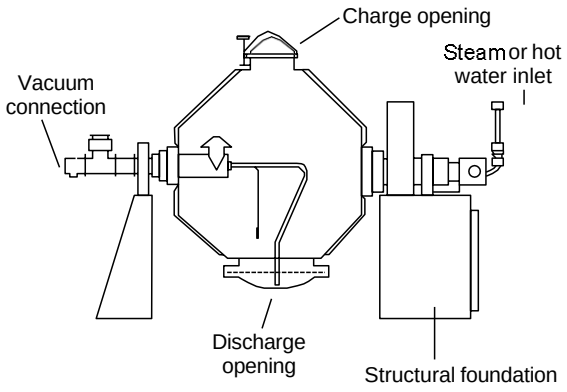


FIGURE 6.3 Rotating batch vacuum dryer.

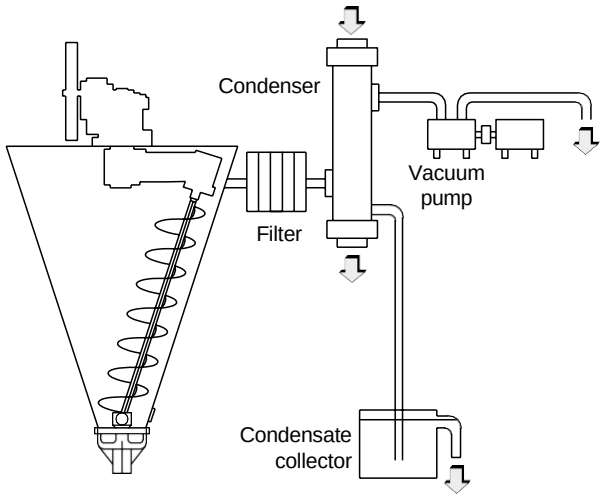


FIGURE 6.4 Cone dryer.

largely on the resistance between the inner jacket wall and the drying solids, which depends to a large extent on the solid characteristics. The overall heat transfer coefficients may drop considerably if the dryer walls are fouled; the values in the range of 5 – 10 W/(m^2 K) are not uncommon.

6.3.4 Agitated Dryers

The first type of agitated dryers is the vertically agitated dryer (shown in Figure 6.4 as a cone dryer). Batch cone dryer (or conical mixer dryer) is a conic- ally shaped vessel, with capacities ranging from 50 l to 25 m^3, and is commonly used for drying solvent or water-wet, free-flowing pharmaceuticals, and fine chemical products, so the dryer is normally operated under vacuum. Agitating action is provided by an internally mounted screw, which can be heated to provide additional heating (possibly in the range of 10 – 30%) to that available through the vessel wall, which rotates about its own axis and also moves around the dryer on an orbiting arm. The distance between the screw and the vessel wall is kept small so that the layer of material on the heating surface is continually renewed. As the screw rotates around the full circumference of the vessel it also provides self- cleaning for the vessel walls as well. The cover is also normally heated to avoid vapor condensation in the process area. To avoid contamination of the product good sealing of bearings is an important consideration (Oakley, 1997).

The heating medium for this type of dryer is either hot water, steam, or hot oil in the temperature range of 50 – 150°C and pressure in the range of 3 – 30 kPa absolute. The vapor generated during drying is evacuated by a vacuum pump and, if necessary, passed

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