

The Ins and Outs Of Indirect Drying

Consistent with the diversity of chemical-process-industries materials that undergo drying, a wide variety of contact dryers have been brought to the marketplace. However, there is a common set of principles for their process design, and for specifying them

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Drying is the unit operation whereby, through heating, volatile substances are removed from a single non-volatile material or a mixture of them, producing a final product relatively or completely free of volatiles. In most applications, the volatile substances are organic solvents or water or a mixture of both. The final product may be of powdery, granular, pasty, or viscous consistency.

Since heat is applied to effect the separation, drying is a thermal separation unit operation. It finds use in virtually all process industries. Different products are dried in a large variety of dryers. Even so, dryers can be classified according to the manner the heat is transferred to the moist material in convective contact, radiation or infrared, dielectric, vacuum or freeze dryers.

The tremendous diversity of applications has made it somewhat difficult to develop a general theoretical understanding of the drying behavior of industrial equipment. For the same reason, there is no universal computerized design procedure available. Drying has been and remains a kind of art.

This article focuses on contact or indirect drying, where the heat is transferred to the processed material through a heated surface. It gives general information about some industrial

contact dryers, cites selection criteria for batch and continuous dryers, presents basic design procedures, highlights the necessity of pilot scale testing as basis for the final selection and design of a dryer, and closes with some examples of industrial applications.

CONTACT DRYERS: SOME MAJOR VERSIONS

Contact drying is highly versatile. On the one hand, it can handle material that is very "thin," that is, of low viscosity, or dilute or both [1]. Similarly, flat and strip materials, such as paper, textile or cardboard, pasty or creamy, granular and even highly viscous materials are dried in contact dryers [3, 4].

Contact or indirect dryers, also known as nonadiabatic dryers, are heated by saturated steam, hot water, glycol solutions and commercially available heat-transfer fluids. The last-named can provide heating temperatures up to 360°C. Above that limit indirect firing, electric heating or salts could be considered.

In most cases, indirect dryers do not require the use of sweep gas to remove the vapors released during drying. An exception arises when a very low final content of volatile material must be reached. This is often the case during the drying of polymers, also known as

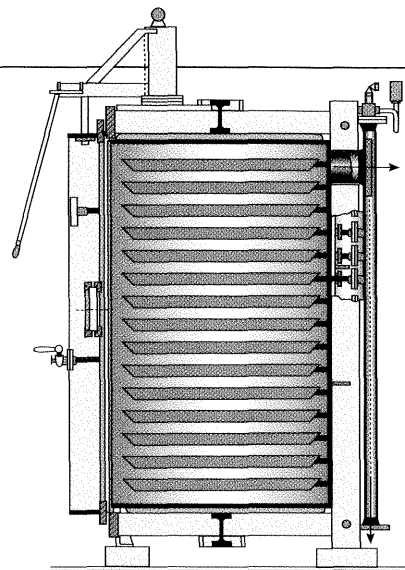


FIGURE 1. Key components of a vacuum tray dryer include a drying chamber, heated shelves, a vapor nozzle, and provision for the heating medium

devolatilization. The presence of the sweep gas reduces the partial pressure of the vapor of the volatile substance, in the environment surrounding the processed material, below that of the equilibrium pressure, enabling drying to progress.

Contact dryers offer several advantages over direct dryers:

- Cross-contamination is avoided because the product does not contact the heat transfer medium
- Solvent recovery is easy, due to the very small amount of noncondensable gas present
- Extensive dust formation is generally avoided, because of the small volume of vapors involved. Admittedly, however, vapor volume can become considerably large and create dusting when operating under low vacuum and high temperature
- Operation under vacuum is possible, preventing product degradation
- These dryers can be of closed design, thus containing toxic vapors and/or providing better control of explosion hazards
- The thermal efficiency, defined as heat required per unit mass of evaporated liquid, is high
- The final product, when granular or powdery, has a higher bulk density than when the same product is dried in a spray dryer
- Contact dryers can be designed as pressure- and shock-resistant vessels
- They usually require less erection space.

Dryers are often built to match the specific drying characteristics of the material to be dried. Accordingly, the

NOMENCLATURE					
A	heat exchange surface	m ²	ΔT	temperature diff.	K
c_p	specific heat	kJ/(kg)(K)	t	time	h
D	diameter	m	U	overall heat transfer coefficient	W/(m ²)(K)
F	force	N	V	volume	m ³
Δh_v	heat of vaporization	kJ/kg	y	liquid mass fraction	-
M_d	torque	Nm			
ṁ	mass rate	kg/h			
n	speed of rotation	min ⁻¹			
P	power	kW			
Q	heat flow	W			
T	temperature	K			
Greek letters			Subscripts and superscripts		
α	heat transfer coeff.	W/(m ²)(K)	bp	boiling point	
$\dot{\gamma}$	shear rate	s ⁻¹	cf	conversion factor	
δ	thickness	m	f	feed	
η	viscosity	Pa•s	l	liquid	
η_{eff}	efficiency	-	p	product	
λ	thermal conductivity	W/(m)(K)	s	solid	
ρ	bulk density	kg/m ³	\sim	mean value	
τ	residence time	h			
φ	fill level	-			

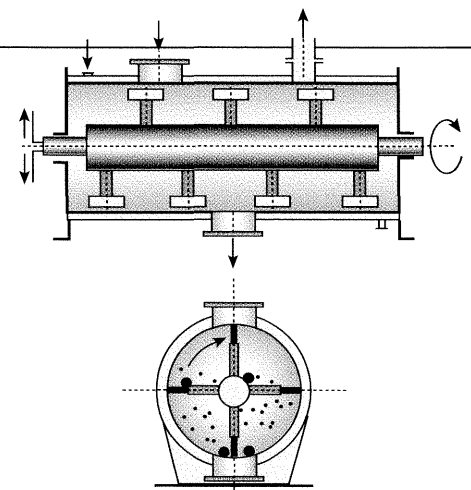


FIGURE 2. Among the components of a batch paddle dryer are its double jacket, shaft, nozzles for feed, discharge and vapor, and provision for heating

number of commercially available contact dryers is very large. A recent market survey performed in Europe registered 45 manufacturers, offering at least as many types of contact dryers. If one would perform a similar survey worldwide, the number would probably be near or even exceed one hundred. With such a number of contact dryers the selection of the optimum one, judged on performance and economy, becomes challenging.

Nevertheless, a number of engineers have looked into algorithms that lead to a preliminary selection of the suitable dryer for a given task [6, 7, 9, 10]. Even with use of algorithms, however, the final selection of the dryer type is usually based on pilot scale drying tests performed with one's original product. We discuss pilot testing in more detail below.

Within the scope of this article, it is hardly possible to cover all types of commercially known contact dryers. Instead, we focus on some representative examples of contact dryers that have found extensive application in the process industries.

Tray and paddle dryers

Figures 1 and 2 show two well known and established types, the vacuum tray dryer and the paddle dryer. Both are nominally batch dryers, although the paddle dryer has also been modified into a continuous dryer. Heating is effected with all industrially common heating media. The feed material is usually a filter cake. The final dry product is coarse, and generally must undergo at least a grinding step. Drying takes place under vacuum.

The tray dryer is selected for small

quantities of expensive products, or for dusty products, or for gentle drying under extremely high vacuum, and for very long drying times.

The tray dryer was later developed into the freeze dryer, and subsequently into the continuous plate dryer. The freeze dryer is mainly applied in the food and pharmaceutical industries. Drying takes place under high vacuum and the volatile substance is removed by sublimation.

That continuous plate dryer cuts the labor intensiveness, and can be designed with several heating sections. Its body is cylindrical, and is installed vertically. Drying takes place preferably under atmospheric pressure. The feed material is a filter cake and flows from the top to the bottom of the unit. A sweep gas, flowing countercurrently to the flow of the processed material, removes the vapors of the volatile substance.

The batch paddle dryer was the first horizontally mounted, agitated dryer. Its body is cylindrical with a length-to-diameter (L/D) ratio that is close to 1. Agitation by the paddles homogenizes the processed material to some extent (although the paddle dryer must not be seen as a blender). The agitation also enhances the heat transfer and the drying rate. The speed of agitation is limited by the mechanical fluidization of the processed material. Should such fluidization arise, the effect of conductivity is considerably reduced, and consequently the heat transfer rate falls. The paddle dryer is preferably operated under vacuum. Heating is provided through the double jacket of the cylindrical shell, the cover plates and the shaft of the agitator.

The agitator of the paddle dryer has seen considerable development. The earliest version is the one shown in Figure 2. It carried radially mounted arms having rectangular paddles welded on them. The orientations of the arms and of the paddles are designed to improve mixing and circulation of processed material in the drying chamber. More-recent designs aim to enhance the heat transfer surface through heating of the arms.

A further development of the paddle dryer is the horizontal rotary vacuum dryer. This dryer can be designed for both batch and continuous operation. The agitator can be ribbonlike, or equipped with plows or scrapers. In continuous units, the agitator's design propels the product axially forward in the drying chamber, from the feed nozzle to the discharge section.

A major disadvantages of the paddle dryer is its tendency to form crust, as well as product lumps. The crust reduces the rate of heat transfer, while the lumps lead to an unevenly dried product. The prevention of crust formation is hardly possible, but the formation of lumps can be lessened through the provision of breaker bars or choppers.

The batch paddle dryer has found wide application throughout the process industries. The feedstock to it can be a filter cake, a coarse granular wet solid material or a slurry. If provision is made to forestall lumps, the final dry product is a free-flowing solid material. The final product discharges through a bottom nozzle equipped with a valve. Particular consideration must be given to the design and specification of that valve. It must provide good seal-

ing against vacuum, avoid dead zones, and prevent obstruction to the free discharge of the final product. In continuous units operated under vacuum, the product discharge is effected by means of a lock discharge unit.

Spiral screw dryers

Engineers realized that to improve the drying performance of the contact dryers, it was necessary to increase the ratio of heat transfer surface to dryer volume (S/V). One of the first developments to achieve this goal was the spiral screw dryer, also known as hollow-flight dryer (Figure 3). The vessel of the dryer has a trough design, providing a vaulted cover to allow for the disengagement of the vapors driven off the solid particles. This dryer is installed horizontally, and incorporates at least two screws. On the screw shafts are welded hollow flights. The heating medium flows through the double jacket of the vessel, the shafts and the flights of the agitators. The screws rotate with identical speed, in either the same or the opposite direction.

The flights of the screws overlap partially and provide some self-cleaning action. This self-cleaning is particularly desirable when one is drying materials that tend to foul the heat transfer surface through the build-up of crust. It should be noted, however, that the self-cleaning effect on the heat transfer surface of the vessel is less effective.

The spiral screw dryer is designed only for continuous operation. Drying takes place preferably under atmospheric pressure, although vacuum operation is also feasible. The feedstock to this drier can be a filter cake, a coarse granular wet solid or even a slurry. The final dry product is a free-flowing solid.

The axial conveyance of the product through the drying chamber depends on the speed of rotation, as well as on the pitch of the screws. As the conveyance rate goes up, the residence time goes down. Therefore, when long residence time is necessary, the required size of the unit becomes quite large. Two units can be operated in series, although with an obvious rise in the capital cost.

FIGURE 3. Spiral screw dryers employ hollow screw conveyors through which the heating medium flows

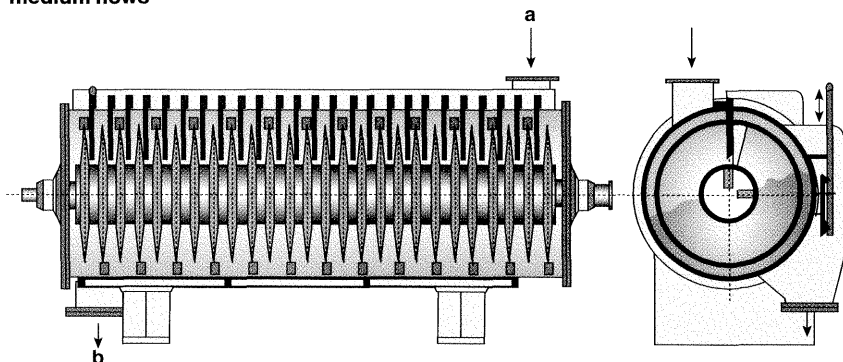
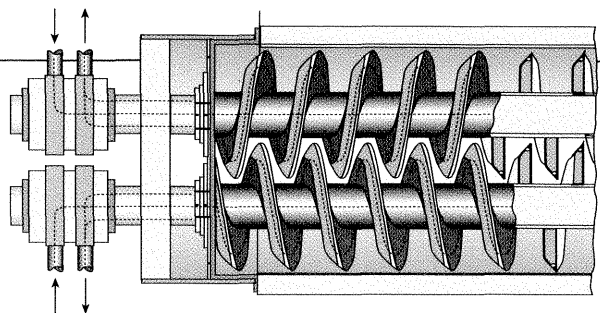


FIGURE 4. In disc dryers, the agitator shaft usually constitutes virtually all of the heat transfer surface; the housing is ordinarily not heated

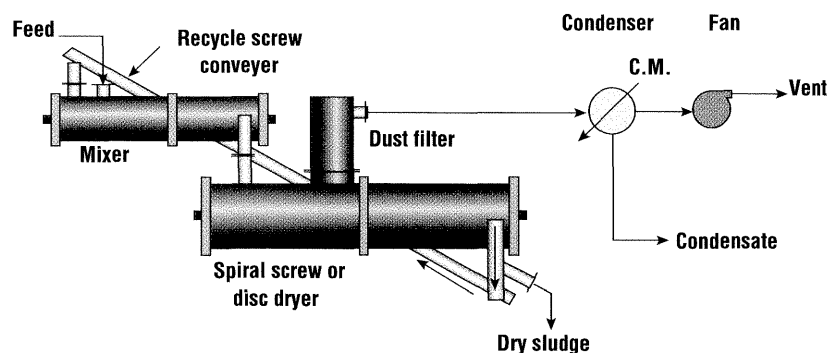


FIGURE 5. The drying of sewage sludge is a well-known application for disc dryers

Disc dryers

The disc dryer (Figure 4) maximizes the S/V ratio in a single unit. It is horizontally mounted. Its shell is of trough design, although a cylindrical form is also feasible. The top cover of the trough is vaulted, allowing the disengagement of the vapors. On the agitator shaft are mounted hollow full discs that, like the shaft itself, can be heated by saturated steam or any thermal fluid. At the periphery of each disc is provided some sort of paddle that enhances the axial conveyance of the product along the chamber of the dryer. In some designs, the disc dryer provides breaker bars and scrapers to improve the mixing of the solids and to provide some cleaning effect on the discs. The agitator shaft accounts for almost 100% of installed heat transfer surface. For this reason the housing of a disc dryer is usually not heated.

The disc dryer is designed only for

continuous operation. The unit is usually operated under atmospheric pressure, although vacuum operation is also feasible. As with the spiral screw dryer, the feedstock can be a filter cake, a coarse granular wet solid or a slurry, and the final dry product is free-flowing.

The conveyance rate of the product through the drying chamber is independent to the speed of rotation. The large volume of this dryer allows drying of materials requiring long residence time, as well as large processing capacities.

A common disadvantage of the spiral screw dryer and the disc dryer is their poor performance when drying pastes or slurries that exhibit an intermediate viscous or sticky phase. That issue arises in a well-known application of the disc dryer, the drying of sewage sludge (Figure 5). To suppress the development of an intermediate

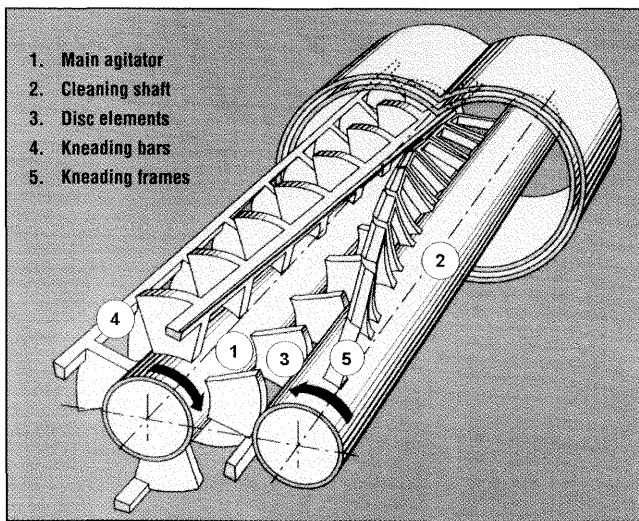


FIGURE 6. The AP kneader-dryer employs a main agitator as well as a cleaning shaft, as well as discs plus kneading bars and kneading frames

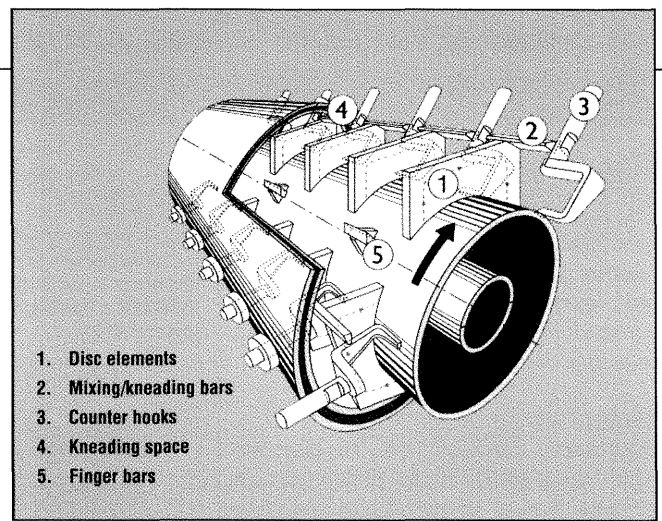


FIGURE 7. This single-shaft kneader-dryer is available in either continuous or batch versions. Stationary, hook-shaped bars help to clean the rotating elements

viscous phase, the wet feed stream is thoroughly mixed with either an inert dry particulate material or with recycled dry sludge. The mixing takes place in a continuous mixer upstream of the feed nozzle of the dryer.

Two proprietary further developments of the disc-dryer concept are the twin-screw paddle dryer and the horizontal thin-film dryer.

As with the screw and disc dryers, the housing of the twin-screw paddle dryer is of trough design, providing a vaulted cover for vapor disengagement. The shafts rotate in the same direction, with identical speeds of rotation. On both agitators shafts are positioned hollow paddles, which are oriented to ensure axial conveyance of the product in the drying chamber.

The agitator shafts and the hollow paddles are heated. If the trough is built with a double jacket, it can also be heated. On the leading edges of the paddles are positioned bars that enhance the local mixing of the material and the overall heat transfer rate. The dryer is preferably used for drying filter cakes and wet granular materials.

The thin film dryer differs from all other paddle, screw or disc dryers in that the shaft rotates in high speed: three to ten times the velocity at which the gravity force on the particles is in balance with the centrifugal force. This dryer employs a horizontal, jacketed, cylindrical shell containing the agitator. The agitator carries a large number of narrow, flat, pitched blades. The configuration of the blades is usually adjusted to the characteristics of the drying process. Thus, it is possible to choose a pitch that either accelerates or retards the convey-

ing velocity of the product in the drying chamber.

A specific design characteristic of this dryer is its mechanism for distributing the feed stream on the heated walls of the shell. The feed stream is evenly distributed and, under the effect of the high rotation speed of the shaft, the product forms a thin layer all along the heated walls of the shell. Because the product is held in the dryer in as a thin layer, the holdup and the residence time are both brief. Nevertheless, the drying efficiency of the thin film dryer is high, due to the high overall heat transfer rate that results from the turbulent conditions prevailing in the thin product layer. The turbulent conditions are ensured from the high speed of rotation.

The thin-film dryer is also used with filter cakes, granular wet materials or slurries. As with all other paddle dryers, the thin film dryer is not effective with materials that go through a viscous phase during processing.

In fact, virtually without exception, all the types of paddle dryers described above are not effective in drying materials that undergo multiple phase changes from liquid to highly viscous, paste en route to the final (usually) free-flowing solid. Such behavior in many cases leads to further complications with side effects, such as foaming, stickiness or crust formation, difficult product flow in the drying chamber, and fluctuation of product temperature and power uptake. When phase changes arise, they can impact the overall heat transfer rate, and therefore the specific drying capacity and the drying time, as well as the uni-

form product distribution in the dryer and the product homogeneity. For such difficult drying processes, specialized contact kneader-dryers have been designed.

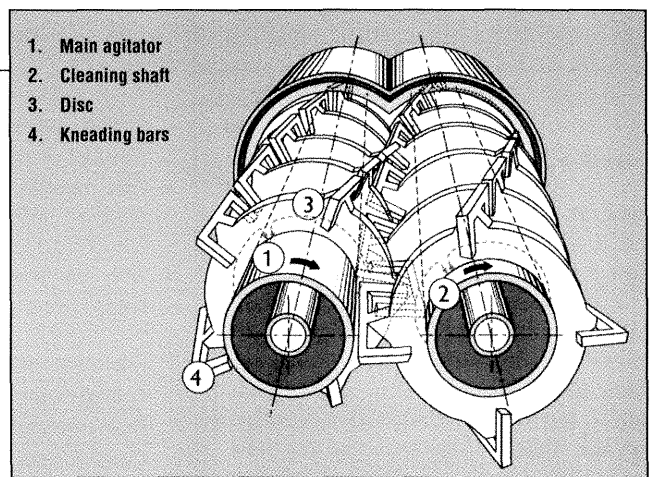
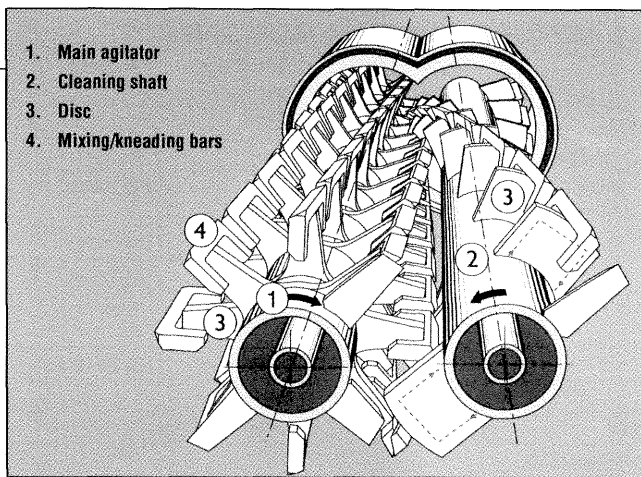
Contact kneader-dryers

Among the first contact kneader-dryers was the all-phases (AP) continuous twin-shaft model (Figure 6). Next came continuous or batch single-shaft types (Figure 7). Eight years ago were developed the twin-shaft, contact, opposite-rotating processor (ORP, Figure 8), only for continuous operation, and the continuous or batch co-rotating processor (CRP, Figure 9).

Single- or twin-shaft contact kneader-dryers are positioned between straightforward screw type equipment and conventional paddle or disc dryers. They combine the effective mixing action of ribbon or plows type units with capacities and heat transfer areas comparable to those of the paddle or disc dryers.

For instance, the single-shaft dryer shown in Figure 7 comprises a horizontal cylindrical shell and a concentric agitator shaft with disc elements perpendicular to the axis carrying peripheral mixing/kneading bars. Stationary hook-shaped bars interact with and clean the shaft and disc elements as they rotate.

AP, ORP and CRP machines have two parallel, intermeshing agitator shafts rotating in a horizontal housing of a roughly figure-eight cross-section (Figures 6, 8 and 9). The main agitator employs radially arranged discs that carry U-shaped kneading bars. The second shaft is fitted with kneading disc elements that mesh with, and



FIGURES 8 (left) AND 9 (right). Both the opposite-rotating (left) and co-rotating processors have two parallel, intermeshing shafts rotating in a housing whose cross-section resembles the numeral, eight

clean, the main agitator's discs and bars. Intermeshing of the elements generates an intensive mixing/kneading action and effective self-cleaning. The spiral arrangement of the internals imparts regular axial conveying coupled with intensive lateral mixing.

The shell, agitator shafts, and disc elements of all contact kneader-dryers can be heated or cooled, giving a large S/V ratio. The intensive mixing and kneading action, coupled with self-cleaning of the heating surfaces, combines to break up baked-on crusts, agglomerates and lumps, ensuring a high rate of product surface renewal for both heat and vapor transfer. The kneading and agitation forces are high.

All contact kneader-dryers are easily adapted to changing feed rates or composition. Other common characteristics are these:

- The large working volume, ensuring long residence time for slow, diffusion controlled drying
- Large cross-sectional area, permitting flash evaporation of superheated feed stocks, ensuring low vapor velocities and preventing solid disengagement
- Closed, contained construction, allowing vacuum or pressure operation, handling of toxic, flammable, or hazardous materials.

DRYER DESIGN

The importance of pilot tests

The actual design procedure for either a batch or continuous contact dryer is part of the proprietary know-how of the manufacturer. Nevertheless, the manufacturer needs to establish a reliable basis for both the process and mechanical design of a given dryer. Such a design basis can only be provided from pilot tests on samples of the product to be dried. Accordingly, dryer

Parameter / criterion	Batch operation	Continuous operation
1. Nature of upstream/downstream operations (a) Batch (b) Continuous	(a) Recommended (b) Not recommended	(a) Not recommended (b) Recommended
2. Final product is: (a) Viscous or pasty (b) Free flowing	(a) Not recommended; difficult to discharge (b) Recommended	(a) Recommended (b) Recommended
3. Operating pressure (a) Under pressure (b) Under vacuum	Suitable for either; simple feed and discharge systems, low investment	For either, specialized feed and discharge systems are needed; high costs
4. Multistage processes, with varying pressures	Recommended	Not possible in one unit
5. Required residence time (a) < 3 hours (b) >3 ~5 hours	(a) Recommended (b) Recommended	(a) Recommended (b) Not recommended
6. Highly viscous phase	Not recommended, because heavy duty drives are necessary with high energy consumption	Recommended; light duty drives are acceptable, with low energy consumption
7. Processing capacity	For low to medium capacities	For medium to high capacities
8. Shift operation (1-2 per day)	Feasible, flexible, recommended	Not recommended
9. Multiproduct operation	Recommended; can handle various products	Not recommended, because not easily adjustable to various products

manufacturers possess pilot facilities, and occasionally make them available to customers on a rental basis.

Pilot tests allow a systematic investigation of the parameters (such as temperature) of the drying process for a particular feed. These tests aim to locate the optimal operating conditions and dryer design characteristics for achieving the targeted final-product quality in the shortest possible drying time.

A detailed parametric investigation is best served running a series of pilot tests in the batch mode. Batch pilot

tests are quick, and require relatively small amounts of raw material. Furthermore, if the full-scale drying unit is also to be batch, then the results of the pilot test also constitute the basis needed for the actual design.

If the full-scale dryer is instead to be continuous, then continuous pilot testing is recommended. In order to perform continuous tests realistically, one must provide the peripheral equipment for feed and discharge. If the dryer manufacturer offers continuous pilot units for rental, it is a good idea to test the performance of the pilot

unit at the customer's site, operating on a slipstream from the production line for the product that is to be dried.

A difference between batch and continuous pilot tests is that parameters measured during the batch tests are time dependent, whereas those measured during continuous tests depend on the distance downstream the feed point. What's more, continuous pilot tests are not only time and product consuming, but also more expensive than batch pilot tests. In relatively straightforward situations, it may be possible to make the design calculations for continuous full-scale drying units based on measurements and other results of batch pilot tests, provided that the dryer manufacturer is experienced and employs reliable design procedures.

Whether the pilot tests are batch or continuous, a key object of carrying them out is to come up with characteristic drying curves for the product, under a variety of operating conditions and dryer geometries. If possible, it is also helpful to have drying data from existing, full-scale operating dryers.

A reasonable design calculation requires the provision of key data concerning the product to be dried (Table 2), the operating conditions (Table 3), the available energy source onsite, the corrosion and abrasion properties of the material, and, last but not least, safety and environmental data (including any relevant regulations) on the product.

Guidelines for dryer design

When all data are in hand, the design basis is fully defined and the scaleup design calculations can be made. Following are some guiding principles leading to the design calculation of the heat exchange surface, the volume of the dryer, and the installed power of his drive unit. For simplicity, it is assumed that the material to be dried consists of a single solid and a single volatile wetting liquid.

For the continuous mode of operation, the dryer can be regarded as consisting of three consecutive sections, for the heating-up, the main evaporation, and the final evaporation. These sections are distinctively seen on the

Data	Feed component	Wetting component	Product
1. Stream composition	Required		Required
2. Amount of wetting component	Required		Required
3. Free, bound, and crystalline water content; sorption isotherm	Required		Required
4. Specific gravity, bulk density	Desirable	Desirable	Desirable
5. Specific heat	Required	Required	Required
6. Melting and softening points, sensitivity to heat	Required		Required
7. Explosive limits	Required	Required	Required
8. Boiling point		Required	
9. Heat of vaporization		Required	
10. Consistency, flow properties, tendency to adhere	Required		Required
11. Plasticization by shearing effects	If applicable		If applicable

Parameter	Comment
1. Mode of operation; number of shifts per day	1. Continuous or batch
2. Hourly or daily capacity	2. Feedrate (continuous) or batch size (batch)
3. Operating pressure	3. Positive pressure, ambient, or vacuum
4. Protection against explosive hazards	4. Relevant for electrical connections
5. Multiproduct operation; product changes	5. Relevant for batch dryers

drying rate curve. The heat flows for each section are calculated applying Equations (1) to (3).

$$\dot{Q}_{\text{heat-up}} = [\dot{m}_s \times c_{ps} + \dot{m}_1 \times c_{p1}] \times \Delta T_1; \quad (1)$$

$$\Delta T_1 = T_{bp1} - T_f$$

$$\dot{Q}_{\text{evap}} = y \times \dot{m}_1 \times \Delta h_{v1} \quad (2)$$

$$\dot{Q}_{\text{acc}} = [\dot{m}_s \times c_{ps} + (1-y) \times \dot{m}_1 \times c_{p1}] \times \Delta T_2; \quad \Delta T_2 = T_p - T_{bp1} \quad (3)$$

In addition, however, special attention must be given to the mechanical dissipation energy. It can become significant, especially when drying materials that pass through a highly viscous phase (for instance, when drying polymers). In some case, the dissipation energy can even contribute a significant portion of the energy required for drying. If the dissipation energy is ignored, there may be an unforeseen rise in the product temperature, and even a degradation in the product quality. The dissipation energy can only be determined from pilot tests, where the torque applied on the agitator shaft is monitored (Equation 4).

$$\dot{Q}_{\text{mech}} = \frac{1}{cf} \times M_d \times n; \quad cf = \text{conversion factor} \quad (4)$$

In Equation (4), the torque, M_d , depends on the specific type of dryer, the viscosity of the dried product, its hold-up, the speed of rotation, and the shear rate:

$$M_d \propto f \left(\begin{array}{l} \text{holdup, } \eta, \dot{\gamma}, n, \\ \text{geometry, type of dryer} \end{array} \right) \quad (5)$$

If free flowing particulate products are dried, the torque can be calculated according to the following formula:

$$M_d = F_{\text{frictions}} \times \frac{D}{2} \quad (6)$$

The total heat exchange surface required is calculated from Equation (7):

$$A = \sum \left(\begin{array}{l} \frac{\dot{Q}_{\text{heat-up}} - \dot{Q}_{\text{mech}}}{\bar{U}_{\text{heat-up}} \times \Delta \bar{T}_{\text{heat-up}}} + \\ \frac{\dot{Q}_{\text{evap}} - \dot{Q}_{\text{mech}} + \dot{Q}_{\text{acc}} - \dot{Q}_{\text{mech}}}{\bar{U}_{\text{evap}} \times \Delta \bar{T}_{\text{evap}} + \bar{U}_{\text{acc}} \times \Delta \bar{T}_{\text{acc}}} \end{array} \right) \quad (7)$$

For the batch mode of operation, the limiting parameter is the net batch time, namely, the time required for the drying operation (excluding the time for feeding and discharging the dryer). Therefore, the heat exchange surface of the batch dryer has to be accordingly selected in order to match the net batch cycle.

$$t_{\text{net batch}} = \sum \frac{1}{A} \left(\begin{array}{l} \frac{\dot{Q}_{\text{heat-up}} - \dot{Q}_{\text{mech}}}{\bar{U}_{\text{heat-up}} \times \Delta \bar{T}_{\text{heat-up}}} + \\ \frac{\dot{Q}_{\text{evap}} - \dot{Q}_{\text{mech}} + \dot{Q}_{\text{acc}} - \dot{Q}_{\text{mech}}}{\bar{U}_{\text{evap}} \times \Delta \bar{T}_{\text{evap}} + \bar{U}_{\text{acc}} \times \Delta \bar{T}_{\text{acc}}} \end{array} \right) \quad (8)$$

The mean U and ΔT values are measured experimentally. Nevertheless, correction factors must also be

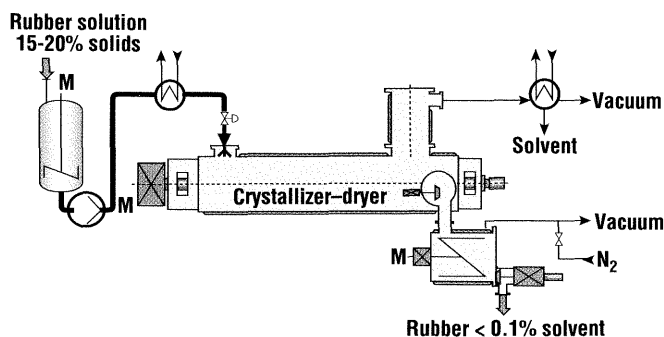


FIGURE 10. The focal point in this flow diagram is the continuous crystallizer-dryer, with overhead solvent removal and recovery of the product elastomer crystals

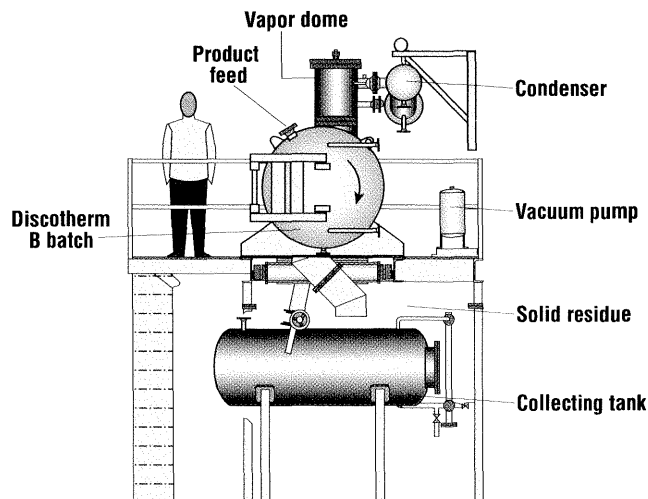


FIGURE 11. This batch system evaporates and dries residues from the processing of rubber. It can handle 750 kg of feed at a time

considered to account for fouling as well as for fluctuations in the product properties and composition and in the operating conditions.

The mean overall heat transfer coefficient, as defined by Equation (9), is particularly sensitive to the thickness of the crust (δ_{crust}) formed on the heat exchange surfaces. It is on the one hand the self cleaning effect of the internals, and on the other hand the provision of small clearances between rotating and stationary parts, that limit the negative effect of the crust formation.

Also, the speed of rotation has a positive effect on the mean overall heat transfer coefficient. Investigations with wet particulate materials have showed a linear relationship between the two. The positive effect of the speed of rotation becomes important at low moisture contents.

$$\frac{1}{\bar{U}} = \frac{1}{\alpha_i} + \frac{\delta_{crust}}{\lambda_{crust}} + \frac{\delta_{wall}}{\lambda_{wall}} + \frac{1}{\alpha_o} \quad (9)$$

The volume of the dryer is directly correlated with the heat exchange surface. The volume, significant for both continuous and batch drying processes, defines the residence time of the process product, which can be a limiting parameter for either temperature sensitive materials, or diffusion controlled drying processes, and often for both. The residence time is defined by Equation (10).

$$\tau = \frac{V \times \varphi \times (\rho_f + \rho_p)}{(\dot{m}_f + \dot{m}_p)} ; 0.4 \leq \varphi \leq 0.8 \quad (10)$$

Finally, the installed drive power is calculated as follows:

$$P = \frac{M_d \times n}{cf \times \eta_{eff}} ; cf = \text{conversion factor and} \\ \eta_{eff} = \text{motor efficiency} \quad (11)$$

TYPICAL APPLICATIONS IN THE PROCESS INDUSTRIES

Drying of a crystalline mass

Continuous crystallization by flash evaporation, followed by drying (devolatilization) is a processing sequence that can widely arise. Two diverse examples are the production of sugar substitutes (sugar alcohols) in the food industry, and the crystallization of polymers in the plastics or rubber industries.

In this process the feed stream is a low-viscosity, pumpable solution. It consists of at least two components, one of which is volatile. At the operating pressure, flash evaporation occurs when the feed temperature is higher than the boiling temperature of the volatile component. Following the flash evaporation, crystallization begins after the solution becomes supersaturated. The process stream accordingly becomes a wet mass of crystals.

The further separation of the volatile component from the solid is achieved by means of drying (devolatilization). This can be a time consuming operation, whose duration is mainly set by the time needed for diffusion of the volatile component from the solid matrix to its surface.

Figure 10 shows a representative process flow diagram for the continuous crystallization by flash evaporation, followed by drying and devolatilization, of a specialty grade of elastomer. The process takes place under vacuum at

moderate temperature. The feed stream contains 80 to 85% by weight solvent and 15 to 20% by weight elastomer. The final solvent content must be less than 0.1% by weight.

The process is carried out in a single-shaft kneader-dryer of the type shown in Figure 7, in one-through single stage operation without solids recycling. The feed system consists of the feed pump followed by the flash valve. As the feed stream enters the process chamber, it flashes immediately. The solvent vapors flow through a vapor dome before reaching the condenser and the vacuum pump. The final crystalline elastomer product is discharged through the lateral discharge head of the processor. The design of the processor allows the control of the product fill level in the process chamber. The product is discharged to the product silo by means of a lock discharge vessel.

Flash evaporation generates a large volume of vapors. Such volumes could ordinarily lead to high vapor velocity, which in turn could result in entrainment of liquid droplets and fine crystalline particles. Entrainment is prevented by having a large cross-sectional area available for the disengagement of the vapors.

Crystallization by flash evaporation forms deposits, and excessive fouling on the heat exchange surface is inevitable. Conventional processing equipment would recycle solid material (as in Figure 5) in order to induce supersaturation, thus preventing crust formation, fouling and the risk of blocking the dryer. By contrast, specialized kneader-dryers feature a self-

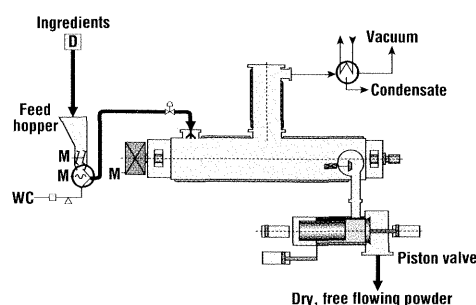


FIGURE 12. Continuous evaporation and drying of block milk, with an intermediate phase change, takes place in this single-shaft unit

cleaning capability as well as intensive mixing, thus allowing the uninterrupted efficient processing of all product phases.

Batch-drying rubber residues

Among the byproducts of rubber processing operations is a mixture of elastomeric components in water and toluene. The water/toluene content of these mixtures can be as high as 70% by weight. Depending on the water/toluene content, the flow properties vary from low-viscosity pumpable solutions to highly viscous pastes. The process material, regardless of its initial rheological status, exhibits a lengthy, highly viscous, rubbery intermediate phase during evaporation. When the evaporation step is nearly completed, that intermediate phase changes into a crumbly rubbery consistency, which is then further dried to a maximum residual water and toluene content of 5% by weight.

Though the initially low viscosity of some production residues could allow the use of a simple evaporators, the formation of the intermediate, highly viscous rubbery phase does not permit their use. Furthermore, the presence of toluene demands that the process takes place under vacuum and nitrogen blanketing.

The evaporation and drying steps take place in a versatile, single-shaft kneader-dryer. Like that for the previous example, the version shown in Figure 7 is employed; but in this case, the equipment is batch rather than continuous. The operating unit is skid mounted. The unit is sized so that it

can be operated for one shift (8 h) per day, at various heating temperatures and vacuum levels that depend on the composition and the boiling temperatures of the volatile components. If desired, the unit can be of modular and mobile design, thus allowing its application at the point of origin of the residues.

Figure 11 shows a layout of a single-shaft, batch kneader-dryer for this service. The unit can handle 750 kg of residues per batch, for feeds with initial solids contents of 30% by weight. Volatiles recovery per batch is 515 kg. The final dry residue has a free flowing consistency and a residual volatiles content of slightly under 5% by weight. The unit can be operated in the absolute-pressure range of 100 millibar to 1 atm., and at a heating temperature of 180°C.

Drying of block milk

Block milk, also known as milk crumb, is a raw material used in chocolate production, pastry cooking and the dairy industries. It is a mixture of concentrated milk, sugar, and cocoa paste. It can be considered a seasonal product, because milk production peaks between spring and autumn. To facilitate its storage, block milk is dried.

Block milk forms when the feed mixture is dried under vacuum and moderate temperatures, from an initial moisture content of about 30% by weight down to the final moisture content around 1.5%. Moderate temperature is applied, to prevent degradation of the milk.

Figure 12 shows the flow diagram for this continuous-drying application. The feed stream is a slightly viscous and sticky but pumpable fluid. It is fed into a single-shaft kneader-dryer of the same type as those in the two previous examples. As drying progresses, the stream enters into a rather pasty phase before becoming a free flowing, crumbly material. The final product is discharged by means of a specially designed piston lock that ensures virtually perfect sealing between drying chamber and discharge to an atmospheric product silo. Meanwhile, the water vapors pass

through a filter before being condensed.

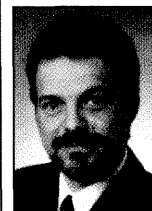
The quality of the product is judged by its taste and by the crystallinity (texture) of contained sugar. The so-called Maillard reaction, which takes place simultaneously with the drying, is responsible for the quality of the taste. The crystallinity of the sugar is ensured from the controlled drying conditions.

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