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furnaces can be treated in the same manner as discussed for batch equipment.

Ceramic tunnel kilns handling large irregular-shaped objects must be equipped for precise control of temperature and humidity conditions to prevent cracking and condensation on the product. The internal mechanism causing cracking when drying clay and ceramics have been studied extensively. Information on ceramic tunnel kiln operation and design is reported fully in publications such as *The American Ceramic Society Bulletin, Ceramic Industry,* and *Transactions of the British Ceramic Society.*

Another use of tunnel dryers is for drying leather. Moisture content is initially around 50 percent but must not be reduced below about 15 percent, or else the leather will crack and be useless. To avoid this, a high-humidity atmosphere is maintained by gas recycle, giving a high equilibrium moisture content.

Continuous Through-Circulation Band Dryers Continuous through-circulation dryers operate on the principle of blowing hot air through a permeable bed of wet material passing continuously through the dryer. Drying rates are high because of the large area of contact and short distance of travel for the internal moisture.

The most widely used type is the **horizontal conveyor dryer** (also called perforated band or conveying-screen dryer), in which wet material is conveyed as a layer, 2 to 15 cm deep (sometimes up to 1 m), on a horizontal mesh screen, belt, or perforated apron, while heated air is blown either upward or downward through the bed of material. This dryer consists usually of a number of individual sections, complete with fan and heating coils, arranged in series to form a housing or tunnel through which the conveying screen travels. As shown in the sectional view in Fig. 12-50, the air circulates through the wet material and is reheated before reentering the bed. It is not uncommon to circulate the hot gas upward in the wet end and downward in the dry end, as shown in Fig. 12-51. A portion of the air is exhausted continuously by one or more exhaust fans, not shown in the sketch, which handle air from several sections. Since each section can be operated independently, extremely flexible operation is possible, with high temperatures usually at the wet end, followed by lower temperatures; in some cases a unit with cooled or specially humidified air is employed for final conditioning. The **maximum pressure drop** that can be taken through the bed of solids without developing leaks or air bypassing is roughly 50 mm of water.

Through-circulation drying requires that the wet material be in a state of granular or pelleted subdivision so that hot air may be readily blown through it. Many materials meet this requirement without special preparation. Others require special and often elaborate pretreatment to render them suitable for through-circulation drying. The process of converting a wet solid to a form suitable for through-circulation of air is called **preforming,** and often the success or failure of this contacting method depends on the preforming step. Fibrous, flaky, and coarse granular materials are usually amenable to drying without preforming. They can be loaded directly onto the conveying screen by suitable spreading feeders of the oscillating-belt or vibrating type or by spiked drums or belts feeding from bins.

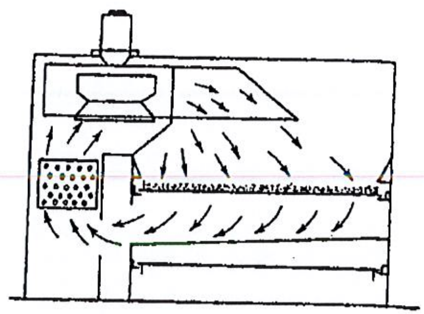

FIG. 12-50 Section view of a continuous through-circulation conveyor dryer. *(Proctor & Schwartz, Inc.)*

When materials must be preformed, several methods are available, depending on the physical state of the wet solid.

1. Relatively dry materials such as centrifuge cakes can sometimes be granulated to give a suitably porous bed on the conveying screen.
2. Pasty materials can often be preformed by extrusion to form spaghettilike pieces, about 6 mm in diameter and several centimeters long.
3. Wet pastes that cannot be granulated or extruded may be predried and preformed on a steam-heated finned drum. Preforming on a finned drum may be desirable also in that some predrying is accomplished.
4. Thixotropic filter cakes from rotary vacuum filters that cannot be preformed by any of the above methods can often be scored by knives on the filter, the scored cake discharging in pieces suitable for through-circulation drying.
5. Material that shrinks markedly during drying is often reloaded during the drying cycle to 2 to 6 times the original loading depth. This is usually done after a degree of shrinkage which, by opening the bed, has destroyed the effectiveness of contact between the air and solids.
6. In a few cases, powders have been pelleted or formed in briquettes to eliminate dustiness and permit drying by through-circulation.

Table 12-20 gives a list of materials classified by preforming methods suitable for through-circulation drying.

Steam-heated air is the usual heat-transfer medium employed in these dryers, although combustion gases may be used also. Temperatures above 600 K are not usually feasible because of the problems of lubricating the conveyor, chain, and roller drives. Recirculation of air is in the range of 60 to 90 percent of the flow through the bed. Conveyors may be made of wire-mesh screen or perforated-steel plate. The minimum practical screen opening size is about 30-mesh (0.5 mm). Multiple bands in series may be used.

Vacuum band dryers utilize heating by conduction and are a continuous equivalent of vacuum tray (shelf) dryers, with the moving

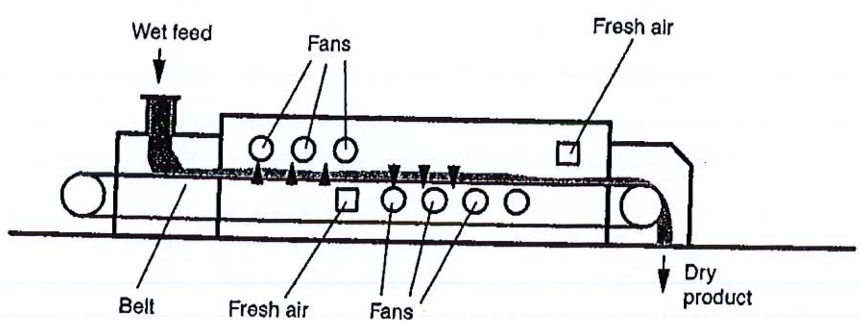

FIG. 12-51 Longitudinal view of a continuous through-circulation conveyor dryer with intermediate airflow reversal.

TABLE 12-21 Experimental Through-Circulation Drying Data for Miscellaneous Materials

		Moisture contents, kg/kg dry solid							
Material	Physical form	Initial	Critical	Final	Inlet-air tempera-ture, K	Depth of bed, cm	Loading, kg product/m^2	Air velocity, m/s × 10^1	Experimental drying time, s × 10^{-3}
Alumina hydrate	Briquettes	0.105	0.06	0.00	453	6.4	60.0	6.0	18.0
Alumina hydrate	Scored filter cake	9.60	4.50	1.15	333	3.8	1.6	11.0	90.0
Alumina hydrate	Scored filter cake	5.56	2.25	0.42	333	7.0	4.6	11.0	108.0
Aluminum stearate	0.7-cm extrusions	4.20	2.60	0.003	350	7.6	6.5	13.0	36.0
Asbestos fiber	Flakes from squeeze rolls	0.47	0.11	0.008	410	7.6	13.6	9.0	5.6
Asbestos fiber	Flakes from squeeze rolls	0.46	0.10	0.0	410	5.1	6.3	9.0	3.6
Asbestos fiber	Flakes from squeeze rolls	0.46	0.075	0.0	410	3.8	4.5	11.0	2.7
Calcium carbonate	Preformed on finned drum	0.85	0.30	0.003	410	3.8	16.0	11.5	12.0
Calcium carbonate	Preformed on finned drum	0.84	0.35	0.0	410	8.9	25.7	11.7	18.0
Calcium carbonate	Extruded	1.69	0.98	0.255	410	1.3	4.9	14.3	9.0
Calcium carbonate	Extruded	1.41	0.45	0.05	410	1.9	5.8	10.2	12.0
Calcium stearate	Extruded	2.74	0.90	0.0026	350	7.6	8.8	5.6	57.0
Calcium stearate	Extruded	2.76	0.90	0.007	350	5.1	5.9	6.0	42.0
Calcium stearate	Extruded	2.52	1.00	0.0	350	3.8	4.4	10.2	24.0
Cellulose acetate	Granulated	1.14	0.40	0.09	400	1.3	1.4	12.7	1.8
Cellulose acetate	Granulated	1.09	0.35	0.0027	400	1.9	2.7	8.6	7.2
Cellulose acetate	Granulated	1.09	0.30	0.0041	400	2.5	4.1	5.6	10.8
Cellulose acetate	Granulated	1.10	0.45	0.004	400	3.8	6.1	5.1	18.0
Clay	Granulated	0.277	0.175	0.0	375	7.0	46.2	10.2	19.2
Clay	1.5-cm extrusions	0.28	0.18	0.0	375	12.7	100.0	10.7	43.8
Cryolite	Granulated	0.456	0.25	0.0026	380	5.1	34.2	9.1	24.0
Fluorspar	Pellets	0.13	0.066	0.0	425	5.1	51.4	11.6	7.8
Lead arsenate	Granulated	1.23	0.45	0.043	405	5.1	18.1	11.6	18.0
Lead arsenate	Granulated	1.25	0.55	0.054	405	6.4	22.0	10.2	24.0
Lead arsenate	Extruded	1.34	0.64	0.024	405	5.1	18.1	9.4	36.0
Lead arsenate	Extruded	1.31	0.60	0.0006	405	8.4	26.9	9.2	42.0
Kaolin	Formed on finned drum	0.28	0.17	0.0009	375	7.6	44.0	9.2	21.0
Kaolin	Formed on finned drum	0.297	0.20	0.005	375	11.4	56.3	12.2	15.0
Kaolin	Extruded	0.443	0.20	0.008	375	7.0	45.0	10.16	18.0
Kaolin	Extruded	0.36	0.14	0.0033	400	9.6	40.6	15.2	12.0
Kaolin	Extruded	0.36	0.21	0.0037	400	19.0	80.7	10.6	30.0
Lithopone (finished)	Extruded	0.35	0.065	0.0004	408	8.2	63.6	10.2	18.0
Lithopone (crude)	Extruded	0.67	0.26	0.0007	400	7.6	41.1	9.1	51.0
Lithopone	Extruded	0.72	0.28	0.0013	400	5.7	28.9	11.7	18.0
Magnesium carbonate	Extruded	2.57	0.87	0.001	415	7.6	11.0	11.4	17.4
Magnesium carbonate	Formed on finned drum	2.23	1.44	0.0019	418	7.6	13.2	8.6	24.0
Mercuric oxide	Extruded	0.163	0.07	0.004	365	3.8	66.5	11.2	24.0
Silica gel	Granular	4.51	1.85	0.15	400	3.8–0.6	3.2	8.6	15.0
Silica gel	Granular	4.49	1.50	0.215	340	3.8–0.6	3.4	9.1	63.0
Silica gel	Granular	4.50	1.60	0.218	325	3.8–0.6	3.5	9.1	66.0
Soda salt	Extruded	0.36	0.24	0.008	410	3.8	22.8	5.1	51.0
Starch (potato)	Scored filter cake	0.866	0.55	0.069	400	7.0	26.3	10.2	27.0
Starch (potato)	Scored filter cake	0.857	0.42	0.082	400	5.1	17.7	9.4	15.0
Starch (corn)	Scored filter cake	0.776	0.48	0.084	345	7.0	26.4	7.4	54.0
Starch (corn)	Scored filter cake	0.78	0.56	0.098	380	7.0	27.4	7.6	24.0
Starch (corn)	Scored filter cake	0.76	0.30	0.10	345	1.9	7.7	6.7	15.0
Titanium dioxide	Extruded	1.2	0.60	0.10	425	3.0	6.8	13.7	6.3
Titanium dioxide	Extruded	1.07	0.65	0.29	425	8.2	16.0	8.6	6.0
White lead	Formed on finned drum	0.238	0.07	0.001	355	6.4	76.8	11.2	30.0
White lead	Extruded	0.49	0.17	0.0	365	3.8	33.8	10.2	27.0
Zinc stearate	Extruded	4.63	1.50	0.005	360	4.4	4.2	8.6	36.0

to reduce the internal pressure to extremely low levels because of the large vapor volumes thereby created. It is necessary to compromise on operating pressure, considering leakage, condensation problems, and the size of the vapor lines and pumping system. Very few vacuum dryers operate below 5 mmHg pressure on a commercial scale. Air in-leakage through gasket surfaces will be in the range of 0.2 kg/(h·linear m of gasketed surface) under these conditions. To keep vapor partial pressure and solids temperature low without pulling excessively high vacuum, a nitrogen bleed may be introduced, particularly in the later stages of drying. The vapor and solids surface temperatures then fall below the vapor boiling point, toward the wet-bulb temperature.

Vertical Agitated Dryers This classification includes vertical pan dryers, filter dryers, and spherical and conical dryers.

Vertical pan dryer The basic vertical pan dryer consists of a short, squat vertical cylinder (Fig. 12-52 and Table 12-24) with an outer heating jacket and an internal rotating agitator, again with the axis vertical, which mixes the solid and sweeps the base of the pan. Heat is supplied by circulation of hot water, steam, or thermal fluid through the jacket; it may also be used for cooling at the end of the batch cycle, using cooling water or refrigerant. The agitator is usually a plain set of solid blades, but may be a ribbon-type screw or internally heated blades. Product is discharged from a door at the lower side of the wall. Sticky materials may adhere to the agitator or be difficult to discharge.

Filter dryer The basic Nutsche filter dryer is like a vertical pan dryer, but with the bottom heated plate replaced by a filter plate. Hence, a slurry can be fed in and filtered, and the wet cake dried in situ. These units are especially popular in the pharmaceutical industry, as containment is good and a difficult wet solids transfer operation is eliminated by carrying out both filtration and drying in the same vessel. Drying times tend to be longer than for vertical pan dryers as the bottom plate is no longer heated. Some types (e.g., Mitchell Thermovac,

TABLE 12-22 Performance Data for Continuous Through-Circulation Dryers*

	Kind of material					
	Inorganic pigment	Cornstarch	Fiber staple	Charcoal briquettes	Gelatin	Inorganic chemical
Capacity, kg dry product/h	712	4536	1724	5443	295	862
Approximate dryer area, m^2	22.11	66.42	Stage A, 57.04; Stage B, 35.12	52.02	104.05	30.19
Depth of loading, cm	3	4		16	5	4
Air temperature, °C	120	115 to 140	130 to 100; 100	135 to 120	32 to 52	121 to 82
Loading, kg product/m^2	18.8	27.3	3.5; 3.3	182.0	9.1	33
Type of conveyor, mm	1.59 by 6.35 slots	1.19 by 4.76 slots	2.57-diameter holes, perforated plate	8.5 × 8.5 mesh screen	4.23 × 4.23 mesh screen	1.59 × 6.35 slot
Preforming method or feed	Rolling extruder	Filtered and scored	Fiber feed	Pressed	Extrusion	Rolling extruder
Type and size of preformed particle, mm	6.35-diameter extrusions	Scored filter cake	Cut fiber	64 × 51 × 25	2-diameter extrusions	6.35-diameter extrusions
Initial moisture content, % bone-dry basis	120	85.2	110	37.3	300	111.2
Final moisture content, % bone-dry basis	0.5	13.6	9	5.3	11.1	1.0
Drying time, min	35	24	11	105	192	70
Drying rate, kg water evaporated/(h·m^2)	38.39	42.97	17.09	22.95	9.91	31.25
Air velocity (superficial), m/s	1.27	1.12	0.66	1.12	1.27	1.27
Heat source per kg water evaporated, steam kg/kg gas (m^3/kg)	Gas 0.11	Steam 2.0	Steam 1.73	Waste heat	Steam 2.83	Gas 0.13
Installed power, kW	29.8	119.3	194.0	82.06	179.0	41.03

*Courtesy of Wolverine Proctor & Schwartz, Inc.

Krauss-Maffei TNT) invert the unit between the filtration and drying stages to avoid this problem.

Spherical dryer Sometimes called the *turbosphere*, this is another agitated dryer with a vertical axis mixing shaft, but rotation is typically faster than in the vertical pan unit, giving improved mixing and heat transfer. The dryer chamber is spherical, with solids discharge through a door or valve near the bottom.

Conical mixer dryer This is a vertically oriented conical vessel with an internally mounted rotating screw. Figure 12-53 shows a schematic of a typical conical mixer dryer. The screw rotates about its own axis (speeds up to 100 rpm) and around the interior of the vessel (speeds up to 0.4 rpm). Because it rotates around the full circumference of the vessel, the screw provides a self-cleaning effect for the heated vessel walls, as well as effective agitation; it may also be internally heated. Either top-drive (via an internal rotating arm) or bottom-drive (via a universal joint) may be used; the former is more common. The screw is cantilevered in the vessel and requires no additional support (even in vessel sizes up to 20-m^3 operating volume). Cleaning of the dryer is facilitated with CIP systems that can be used for cleaning, and/or the vessel can be completely flooded with water or solvents. The dryer makes maximum use of the product-heated areas—the filling volume of the vessel (up to the knuckle of the dished head) is the usable product loading. In some recent applications, microwaves have been used to provide additional energy input and shorten drying times.

In the bottom-drive system, the vessel cover is free of drive components, allowing space for additional process nozzles, manholes, explosion venting, etc., as well as a temperature lance for direct, continuous product temperature measurement in the vessel. The top cover of the vessel is easily heated by either a half-pipe coil or heat tracing, which ensures that no vapor condensation will occur in the process area.

TABLE 12-23 Conveyor-Screen-Dryer Costs*

Length	2.4-m-wide conveyor	3.0-m-wide conveyor
7.5 m	\$8600/m^2	\$7110/m^2
15 m	\$6700/m^2	\$5600/m^2
22.5 m	\$6200/m^2	\$5150/m^2
30 m	\$5900/m^2	\$4950/m^2

*National Drying Machinery Company, 1996.

Because there are no drive components in the process area, the risk of batch failures due to contamination from gear lubricants is eliminated. However, the bottom joint requires especially careful design, maintenance, and sealing. The disassembly of the unit is simplified, as all work on removing the screw can be done without vessel entry. For disassembly, the screw is simply secured from the top, and the drive components are removed from the bottom of the dryer.

Horizontal Pan Dryer This consists of a stationary cylindrical shell, mounted horizontally, in which a set of agitator blades mounted on a revolving central shaft stirs the solids being treated. They tend to be used for larger batches than vertical agitated or batch rotating dryers. Heat is supplied by circulation of hot water, steam, or Dowtherm through the jacket surrounding the shell and, in larger units, through the hollow central shaft. The agitator can be of many different forms, including simple paddles, ploughshare-type blades, a single discontinuous spiral, or a double continuous spiral. The outer blades are set as closely as possible to the wall without touching, usually leaving a gap of 0.3 to 0.6 cm. Modern units occasionally employ spring-loaded shell scrapers mounted on the blades. The dryer is charged through a port at the top and emptied through one or more discharge nozzles at the bottom. Vacuum is applied and maintained by any of the conventional methods, i.e., steam jets, vacuum pumps, etc.

A similar type, the batch indirect rotary dryer, consists of a rotating horizontal cylindrical shell, suitably jacketed. Vacuum is applied to this unit through hollow trunnions with suitable packing glands. Rotary glands must be used also for admitting and removing the heating medium from the jacket. The inside of the shell may have lifting bars, welded longitudinally, to assist agitation of the solids. Continuous rotation is needed while emptying the solids, and a circular dust hood is frequently necessary to enclose the discharge-nozzle turning circle and prevent serious dust losses to the atmosphere during unloading. A typical vacuum rotary dryer is illustrated in Fig. 12-54. Sealing tends to be more difficult where the entire shell rotates compared to the horizontal pan, where only the central agitator shaft rotates, since the seal diameter is smaller in the latter case. Conversely, a problem with a stationary shell is that it can be difficult to empty the final "heel" of material out of the bottom of the cylinder. If batch integrity is important, this is an advantage for the rotary variant over the horizontal pan.

Heated Agitators For all agitated dryers, in addition to the jacket heated area, heating the agitator with the same medium as the