Psychrometry, Evaporative Cooling, and Solids Drying

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PSYCHROMETRY

EVAPORATIVE COOLING

SOLIDS-DRYING FUNDAMENTALS

SOLIDS-DRYING EQUIPMENT

Nomenclature and Units

In this table, symbols used in this section are defined in a general way. SI and customary U.S. units are listed. Specialized symbols are either defined at the point of application or in a separate table of nomenclature.

Symbol	Definition	SI units	U.S. customary units
A	Area	$\mathrm{m^2}$	$\mathrm{ft^2}$
a	Area	$\mathrm{m^2}$	$\mathrm{ft^2}$
C	Heat capacity	J/kg	Btu/lbm
D	Diameter	m	ft
D	Diffusivity	$\mathrm{m^2/s}$	$\mathrm{ft^2/s}$
d	Thickness	m	ft
E	Potential difference	V	V
F	Void fraction	Dimensionless	Dimensionless
G	Mass velocity	$\mathrm{k/(m^2{\cdot}s)}$	$\mathrm{lbm/(ft^2{\cdot}s)}$
H	Humidity	kg/kg	lbm/lbm
h	Heat-transfer coefficient	$\mathrm{J/(m^2{\cdot}s{\cdot}K)}$	$\mathrm{Btu/(ft^2{\cdot}h{\cdot}{}^\circ F)}$
k	Mass-transfer coefficient	$\mathrm{kg/(m^2{\cdot}s{\cdot}atm)}$	$\mathrm{lbm/(h{\cdot}ft^2{\cdot}atm)}$
K	Thermal conductivity	W/(m·K)	Btu/(ft·h·°F)
L	Length	m	ft
M	Molecular weight	kg/mol	lbm/mol
N	Rotational speed	l/s	l/min
P	Pressure	Pa	$\mathrm{lbf/in^2}$
P	Pressure drop	Pa	$\mathrm{lbf/ft^2}$
Q	Flow rate	$\mathrm{m^3/s}$	$\mathrm{ft^3/s}$
Q	Total heat flow	J/s	Btu/h
S	Slope	m/m	ft/ft
t	Time	s	s, h
t	Temperature	°C	°F
T	Absolute temperature	K	°R
U	Heat-transfer coefficient	$\mathrm{J/(m^2{\cdot}s{\cdot}K)}$	$\mathrm{Btu/(ft^2{\cdot}h{\cdot}{}^\circ F)}$
u	Velocity	m/s	ft/s
V	Velocity	m/s	ft/s
V	Volume	$\mathrm{m^3}$	$\mathrm{ft^3}$
W	Mass	kg	lbm
	Greek symbols		
ϵ	Void fraction	Dimensionless	Dimensionless
θ	Time	s	s, h
λ	Latent heat	J/kg	Btu/lbm
μ	Viscosity	Pa·s	lbm/(s·ft)
ρ	Density	$\mathrm{kg/m^3}$	$\mathrm{lbm/ft^3}$
σ	Surface tension	N/m	dyn/cm

PSYCHROMETRY*

General References: *Handbook of Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1967. Quinn, "Humidity: The Neglected Parameter," *Test Eng.* (July 1968). Treybal, *Mass-Transfer Operations,* 3d ed. McGraw-Hill, New York, 1980. Wexler, *Humidity and Moisture,* vol. I, Reinhold, New York, 1965. Zimmerman and Lavine, Psychrometric Charts and Tables, Industrial Research Service, 2d ed., Dover, N.H., 1964.

Psychrometry is concerned with determination of the properties of gas-vapor mixtures. The air-water vapor system is by far the system most commonly encountered.

Principles involved in determining the properties of other systems are the same as with air-water vapor, with one major exception. Whereas the psychrometric ratio (ratio of heat-transfer coefficient to product of mass-transfer coefficient and humid heat, terms defined in the following subsection) for the air-water system can be taken as 1, the ratio for other systems in general does not equal 1. This has the effect of making the adiabatic-saturation temperature different from the wet-bulb temperature. Thus, for systems other than air-water vapor, calculation of psychrometric and drying problems is complicated by the necessity for point-to-point calculation of the temperature of the evaporating surface. For example, for the air-water system the temperature of the evaporating surface will be constant during the constant-rate drying period even though temperature and humidity of the gas stream change. For other systems, the temperature of the evaporating surface would change.

TERMINOLOGY

Terminology and relationships pertinent to psychrometry are:

Absolute humidity H equals the pounds of water vapor carried by 1 lb of dry air. If ideal-gas behavior is assumed, $H = M_w p/[M_a(P - p)]$, where M_w = molecular weight of water; M_a = molecular weight of air; p = partial pressure of water vapor, atm; and P = total pressure, atm.

When the partial pressure p of water vapor in the air at a given temperature equals the vapor pressure of water p_s at the same temperature, the air is saturated and the absolute humidity is designated the **saturation humidity** H_s.

Percentage absolute humidity (percentage saturation) is defined as the ratio of absolute humidity to saturation humidity and is given by $100\ H/H_s = 100p(P - p_s)/[p_s(P - p)]$.

Percentage relative humidity is defined as the partial pressure of water vapor in air divided by the vapor pressure of water at the given temperature. Thus RH = $100p/p_s$.

Dew point, or **saturation temperature,** is the temperature at which a given mixture of water vapor and air is saturated, for example, the temperature at which water exerts a vapor pressure equal to the partial pressure of water vapor in the given mixture.

Humid heat c_s is the heat capacity of 1 lb of dry air and the moisture it contains. For most engineering calculations, $c_s = 0.24 + 0.45H$, where 0.24 and 0.45 are the heat capacities of dry air and water vapor, respectively, and both are assumed constant.

Humid volume is the volume in cubic feet of 1 lb of dry air and the water vapor it contains.

Saturated volume is the humid volume when the air is saturated.

Wet-bulb temperature is the dynamic equilibrium temperature attained by a water surface when the rate of heat transfer to the surface by convection equals the rate of mass transfer away from the surface. At equilibrium, if negligible change in the dry-bulb temperature is assumed, a heat balance on the surface is

$$k_g \lambda(p_s - p) = h_c(t - t_w) \tag{12-1a}$$

where k_g = mass-transfer coefficient, lb/(h·ft^2·atm); λ = latent heat of vaporization, Btu/lb; p_s = vapor pressure of water at wet-bulb temperature, atm; p = partial pressure of water vapor in the environment, atm; h_c = heat-transfer coefficient, Btu/(h·ft^2·°F); t = temperature of air-water vapor mixture (dry-bulb temperature), °F; and t_w = wet-bulb temperature, °F. Under ordinary conditions the partial pressure and vapor pressure are small relative to the total pressure, and the wet-bulb equation can be written in terms of humidity differences as

$$H_s - H = (h_c/\lambda k')(t - t_w) \tag{12-1b}$$

where k' = lb/(h·ft^2) (unit humidity difference) = $(M_a/M_w)k_g = 1.6k_g$.

Adiabatic-Saturation Temperature, or Constant-Enthalpy Lines If a stream of air is intimately mixed with a quantity of water at a temperature t_s in an adiabatic system, the temperature of the air will drop and its humidity will increase. If t_s is such that the air leaving the system is in equilibrium with the water, t_s will be the adiabatic-saturation temperature, and the line relating the temperature and humidity of the air is the adiabatic-saturation line. The equation for the adiabatic-saturation line is

$$H_s - H = (c_s/\lambda)(t - t_s) \tag{12-2}$$

RELATION BETWEEN WET-BULB AND ADIABATIC-SATURATION TEMPERATURES

Experimentally it has been shown that for air-water systems the value of $h_c/k'c_s$, the **psychrometric ratio,** is approximately equal to 1. Under these conditions the wet-bulb temperatures and adiabatic-saturation temperatures are substantially equal and can be used interchangeably. The difference between adiabatic-saturation temperature and wet-bulb temperature increases with increasing humidity, but this effect is unimportant for most engineering calculations. An empirical formula for wet-bulb temperature determination of moist air at atmospheric pressure is presented by Liley [*Int. J. of Mechanical Engineering Education,* vol. 21, No. 2 (1993)].

For systems other than air-water vapor, the value of $h_c/k'c_s$ may differ appreciably from unity, and the wet-bulb and adiabatic-saturation temperatures are no longer equal. For these systems the psychrometric ratio may be obtained by determining h_c/k' from heat- and mass-transfer analogies such as the Chilton-Colburn analogy [*Ind. Eng. Chem.,* **26,** 1183 (1934)]. For low humidities this analogy gives

$$\frac{h_c}{k'} = c_s \left(\frac{\mu/\rho D_v}{c_s\mu/k}\right)^{2/3} \tag{12-3}$$

where c_s = humid heat, Btu/(lb·°F); μ = viscosity, lb/(ft·h); ρ = density, lb/ft^3; D_v = diffusivity, ft^2/h; and k = thermal conductivity, Btu/(h·ft^2)(°F/ft). All properties should be evaluated for the gas mixture.

For the case of **flow past cylinders,** such as a wet-bulb thermometer, Bedingfield and Drew [*Ind. Eng. Chem.,* **42,** 1164 (1950)] obtained a correlation for their data on sublimation of cylinders into air and for the data of others on wet-bulb thermometers. For wet-bulb thermometers in air they give

$$h_c/k' = 0.294(\mu/\rho D_v)^{0.56} \tag{12-4}$$

where the nomenclature is identical to that in Eq. (12-3). For evaporation into gases other than air, Eq. (12-3) with an exponent of 0.56 would apply.

Application of these equations is illustrated in Example 1.

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* The contribution of Eno Bagnoli, E. I. du Pont de Nemours & Co., to material that was used from the sixth edition is acknowledged. (Psychrometry)

Example 1: Compare Wet-Bulb and Adiabatic-Saturation Temperatures For the air-water system at atmospheric pressure, the measured values of dry-bulb and wet-bulb temperatures are 85 and 72°F respectively. Determine the absolute humidity and compare the wet-bulb temperature and adiabatic-saturation temperature. Assume that h_c/k' is given by Eq. (12-4).

Solution. For relatively dry air the Schmidt number $\mu/\rho D_v$ is 0.60, and from Eq. (12-4) $h_c/k' = 0.294(0.60)^{0.56} = 0.221$. At 72°F the vapor pressure of water is 20.07 mmHg, and the latent heat of vaporization is 1051.6 Btu/lb. From Eq. (12-1*b*), $[20.07/(760 - 20.07)](18/29) - H = (0.221/1051.6)(85 - 72)$, or $H = 0.0140$ lb water/lb dry air. The humid heat is calculated as $c_s = 0.24 + 0.45(0.0140) = 0.246$. The adiabatic-saturation temperature is obtained from Eq. (12-2) as

$$H_s - 0.0140 = (0.246/1051.6)(85 - t_s)$$

Values of H_s and t_s are given by the saturation curve of the psychrometric chart, such as Fig. 12-2. By trial and error, $t_s = 72.1$°F, or the adiabatic-saturation temperature is 0.1°F higher than the wet-bulb temperature.

USE OF PSYCHROMETRIC CHARTS

Three **charts for the air-water vapor system** are given as Figs. 12-1 to 12-3 for low-, medium-, and high-temperature ranges. Figure 12-4 shows a modified Grosvenor chart, which is more familiar to the chemical engineer. These charts are for an absolute pressure of 1 atm. The corrections required at pressures different from atmospheric are given in Table 12-2. Figure 12-5 shows a psychrometric chart for combustion products in air. The thermodynamic properties of moist air are given in Table 12-1.

Examples Illustrating Use of Psychrometric Charts In these examples the following nomenclature is used:

t = dry-bulb temperatures, °F
t_w = wet-bulb temperature, °F
t_d = dew-point temperature, °F
H = moisture content, lb water/lb dry air
ΔH = moisture added to or rejected from the air stream, lb water/lb dry air
h' = enthalpy at saturation, Btu/lb dry air
D = enthalpy deviation, Btu/lb dry air
$h = h' + D$ = true enthalpy, Btu/lb dry air
h_w = enthalpy of water added to or rejected from the system, Btu/lb dry air
q_a = heat added to the system, Btu/lb dry air
q_r = heat removed from system, Btu/lb dry air

Subscripts 1, 2, 3, etc., indicate entering and subsequent states.

Example 2: Determination of Moist Air Properties Find the properties of moist air when the dry-bulb temperature is 80°F and the wet-bulb temperature is 67°F.

Solution. Read directly from Fig. 12-2 (Fig. 12-6 shows the solution diagrammatically).

Moisture content H = 78 gr/lb dry air
= 0.011 lb water/lb dry air
Enthalpy at saturation h' = 31.6 Btu/lb dry air
Enthalpy deviation D = −0.1 Btu/lb dry air
True enthalpy h = 31.5 Btu/lb dry air
Specific volume v = 13.8 ft^3/lb dry air
Relative humidity = 51 percent
Dew point t_d = 60.3°F

Example 3: Air Heating Air is heated by a steam coil from 30°F dry-bulb temperature and 80 percent relative humidity to 75°F dry-bulb temperature. Find the relative humidity, wet-bulb temperature, and dew point of the heated air. Determine the quantity of heat added per pound of dry air.

Solution. Reading directly from the psychrometric chart (Fig. 12-2),

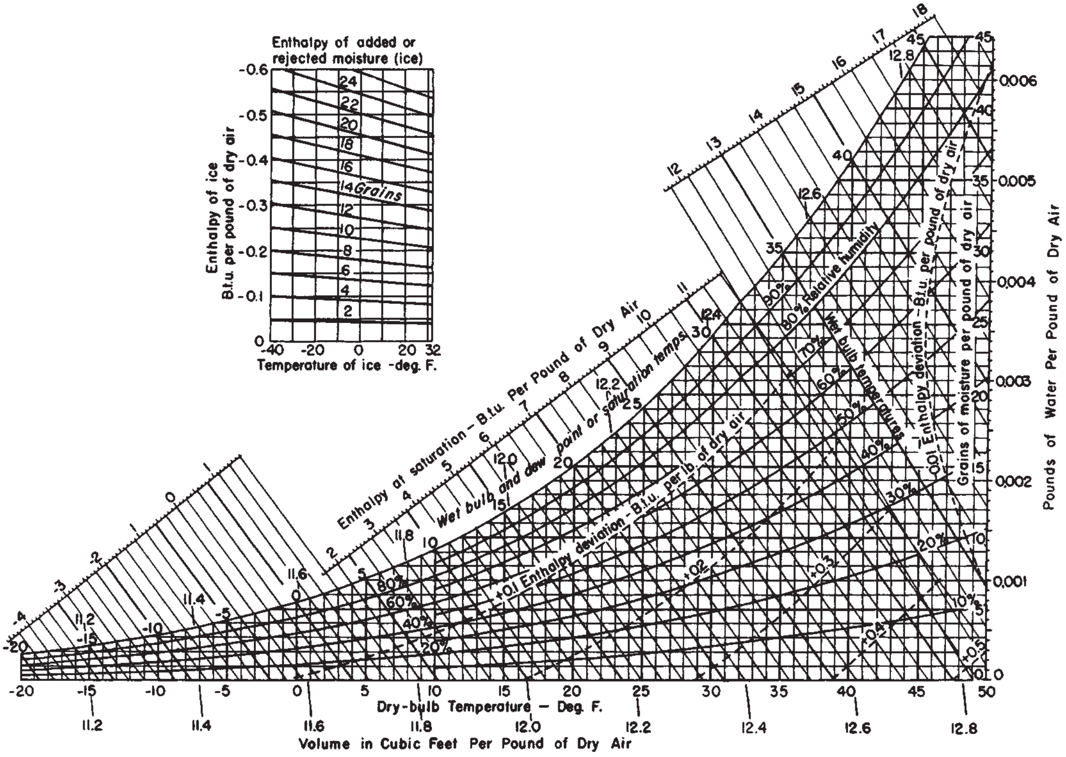

FIG. 12-1 Psychrometric chart—low temperatures. Barometric pressure, 29.92 inHg. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

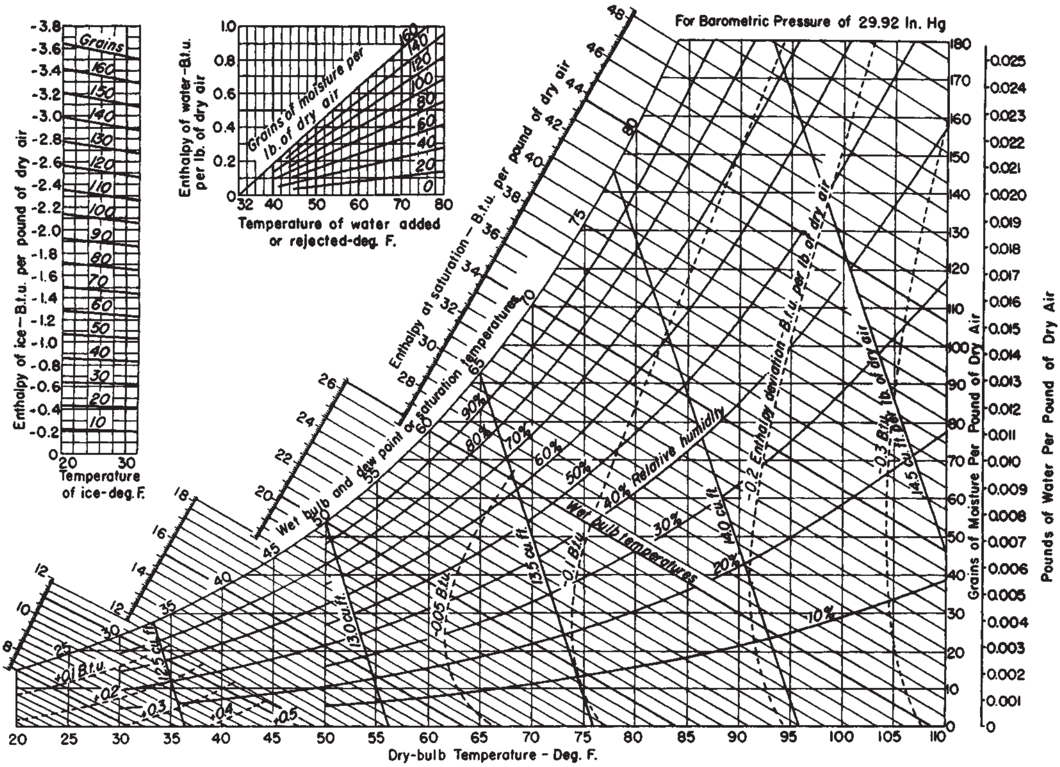

FIG. 12-2 Psychrometric chart—medium temperatures. Barometric pressure, 29.92 inHg. To convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

Relative humidity = 15 percent

Wet-bulb temperature = 51.5°F

Dew point = 25.2°F

The enthalpy of the inlet air is obtained from Fig. 12-2 as $h_1 = h'_1 + D_1 = 10.1 + 0.06 = 10.16$ Btu/lb dry air; at the exit, $h_2 = h'_2 + D_2 = 21.1 - 0.1 = 21$ Btu/lb dry air. The heat added equals the enthalpy difference, or

$$q_a = \Delta h = h_2 - h_1 = 21 - 10.16 = 10.84 \text{ Btu/lb dry air}$$

If the enthalpy deviation is ignored, the heat added q_a is $\Delta h = 21.1 - 10.1 = 11$ Btu/lb dry air, or the result is 1.5 percent high. Figure 12-7 shows the heating path on the psychrometric chart.

Example 4: Evaporative Cooling Air at 95°F dry-bulb temperature and 70°F wet-bulb temperature contacts a water spray, where its relative humidity is increased to 90 percent. The spray water is recirculated; makeup water enters at 70°F. Determine exit dry-bulb temperature, wet-bulb temperature, change in enthalpy of the air, and quantity of moisture added per pound of dry air.

Solution. Figure 12-8 shows the path on a psychrometric chart. The leaving dry-bulb temperature is obtained directly from Fig. 12-2 as 72.2°F. Since the spray water enters at the wet-bulb temperature of 70°F and there is no heat added to or removed from it, this is by definition an adiabatic process and there will be no change in wet-bulb temperature. The only change in enthalpy is that from the heat content of the makeup water. This can be demonstrated as follows:

Inlet moisture $H_1 = 70$ gr/lb dry air

Exit moisture $H_2 = 107$ gr/lb dry air

$\Delta H = 37$ gr/lb dry air

Inlet enthalpy $h_1 = h'_1 + D_1 = 34.1 - 0.22$

$= 33.88$ Btu/lb dry air

Exit enthalpy $h_2 = h'_2 + D_2 = 34.1 - 0.02$

$= 34.08$ Btu/lb dry air

Enthalpy of added water $h_w = 0.2$ Btu/lb dry air (from small diagram, 37 gr at 70°F)

Then $q_a = h_2 - h_1 + h_w$

$= 34.08 - 33.88 + 0.2 = 0$

Example 5: Cooling and Dehumidification Find the cooling load per pound of dry air resulting from infiltration of room air at 80°F dry-bulb temperature and 67°F wet-bulb temperature into a cooler maintained at 30°F dry-bulb and 28°F wet-bulb temperature, where moisture freezes on the coil, which is maintained at 20°F.

Solution. The path followed on a psychrometric chart is shown in Fig. 12-9.

Inlet enthalpy $h_1 = h'_1 + D_1 = 31.62 - 0.1$

$= 31.52$ Btu/lb dry air

Exit enthalpy $h_2 = h'_2 + D_2 = 10.1 + 0.06$

$= 10.16$ Btu/lb dry air

Inlet moisture $H_1 = 78$ gr/lb dry air

Exit moisture $H_2 = 19$ gr/lb dry air

Moisture rejected $\Delta H = 59$ gr/lb dry air

Enthalpy of rejected moisture $= -1.26$ Btu/lb dry air (from small diagram of Fig. 12-2)

Cooling load $q_r = 31.52 - 10.16 + 1.26$

$= 22.62$ Btu/lb dry air

Note that if the enthalpy deviations were ignored, the calculated cooling load would be about 5 percent low.

Example 6: Cooling Tower Determine water consumption and amount of heat dissipated per 1000 ft^3/min of entering air at 90°F dry-bulb temperature and 70°F wet-bulb temperature when the air leaves saturated at 110°F and the makeup water is at 75°F.

Solution. The path followed is shown in Fig. 12-10.

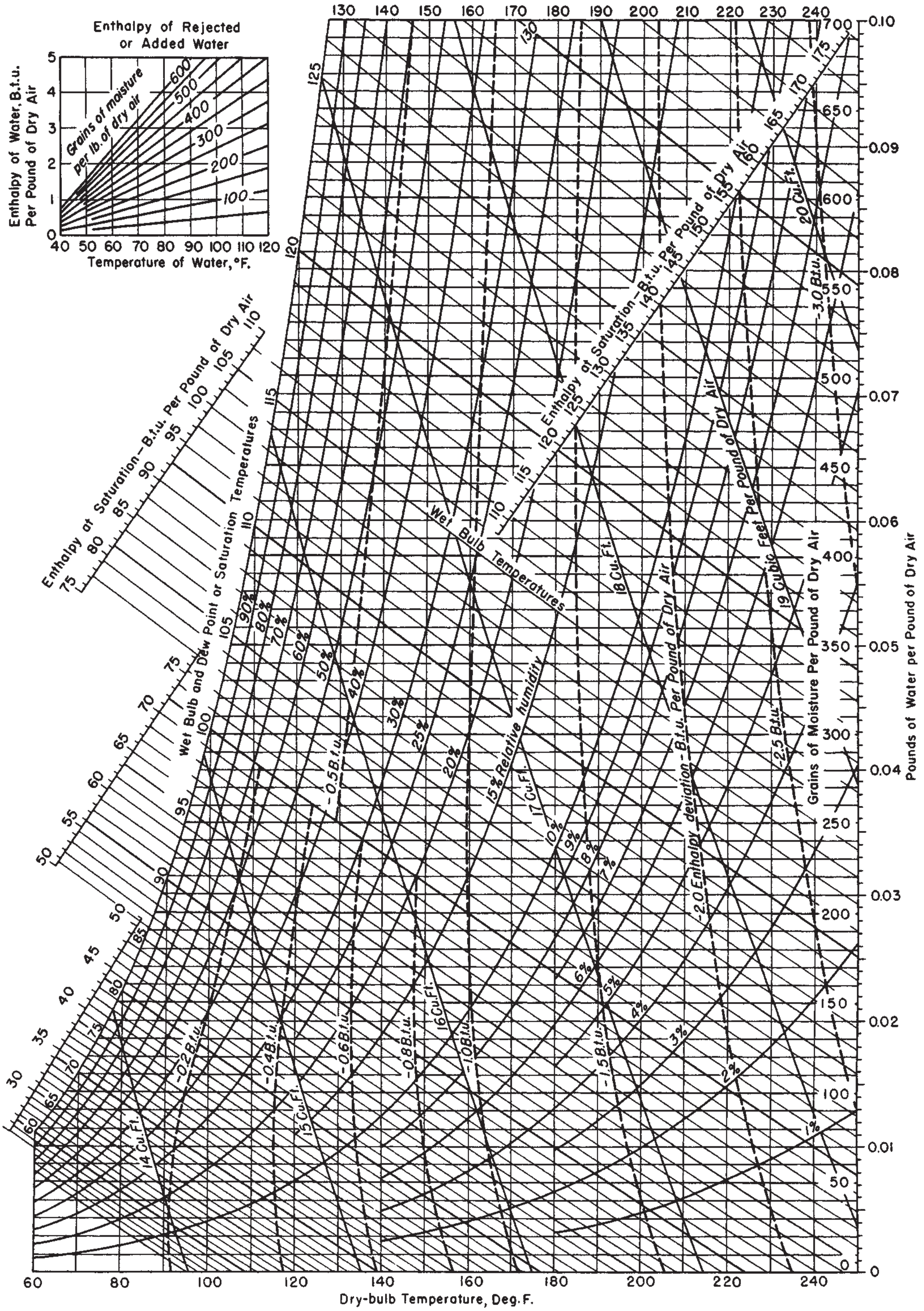

FIG. 12-3 Psychrometric chart—high temperatures. Barometric pressure, 29.92 inHg. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

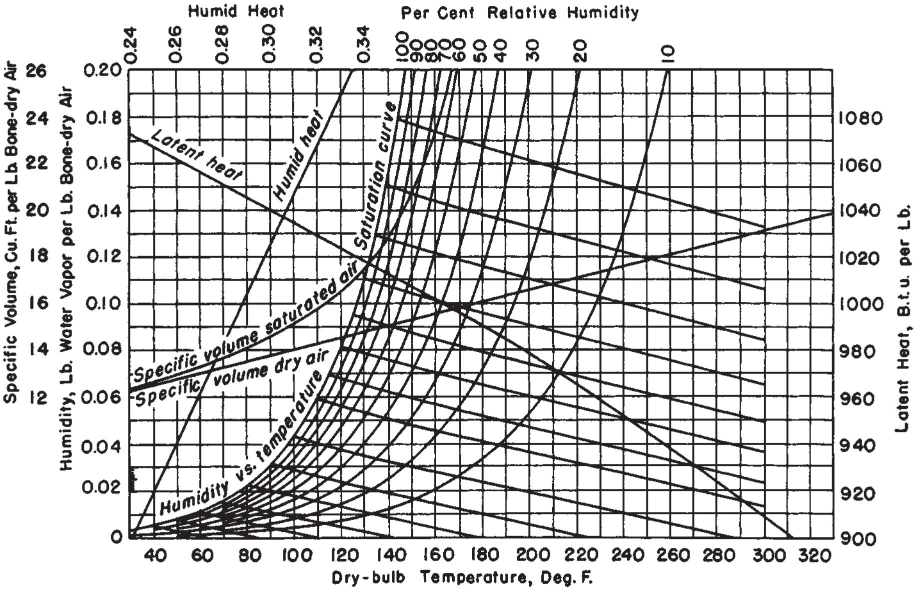

FIG. 12-4 Humidity chart for air-water vapor mixtures. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

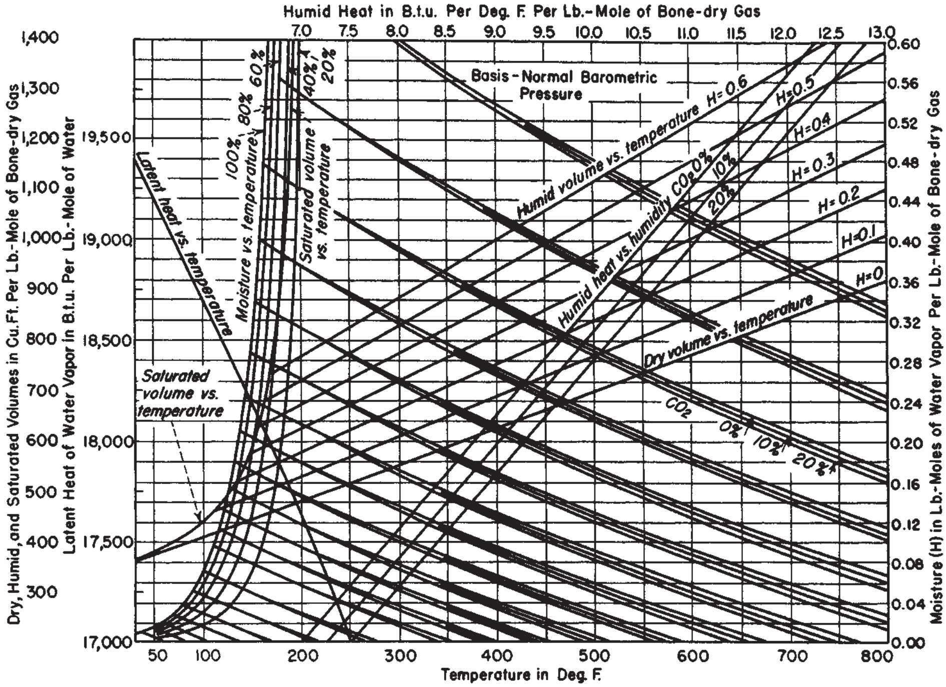

FIG. 12-5 Revised form of high-temperature psychrometric chart for air and combustion products, based on pound-moles of water vapor and dry gases. [*Hatta,* Chem. Metall. Eng., **37,** *64* (*1930*).]

TABLE 12-1 Thermodynamic Properties of Moist Air (Standard Atmospheric Pressure, 29.921 inHg)

Temp.	Saturation humidity	Volume, cu. ft./lb. dry air			Enthalpy, B.t.u./lb. dry air			Entropy, B.t.u./(°F.)(lb. dry air)			Condensed water			Temp.
t, °F.	$H_s \times 10^8$	v_a	v_{as}	v_s	h_a	h_{as}	h_s	s_a	s_{as}	s_s	Enthalpy, B.t.u./lb. h_w	Entropy, B.t.u./(lb.)(°F.) s_w	Vapor press., in. Hg $p_s \times 10^6$	t, °F.
−160	0.2120	7.520	0.000	7.520	−38.504	0.000	−38.504	−0.10300	0.00000	−0.10300	−222.00	−0.4907	0.1009	−160
−155	.3869	7.647	.000	7.647	−37.296	.000	−37.296	−0.09901	.00000	−0.09901	−220.40	−0.4853	.1842	−155
−150	.6932	7.775	.000	7.775	−36.088	.000	−36.088	−0.09508	.00000	−0.09508	−218.77	−0.4800	.3301	−150
−145	1.219	7.902	.000	7.902	−34.881	.000	−34.881	−0.09121	.00000	−0.09121	−217.12	−0.4747	.5807	−145
−140	2.109	8.029	.000	8.029	−33.674	.000	−33.674	−0.08740	.00000	−0.08740	−215.44	−0.4695	1.004	−140
−135	3.586	8.156	.000	8.156	−32.468	.000	−32.468	−0.08365	.00000	−0.08365	−213.75	−0.4642	1.707	−135
−130	6.000	8.283	.000	8.283	−31.262	.000	−31.262	−0.07997	.00000	−0.07997	−212.03	−0.4590	2.858	−130
	$H_s \times 10^7$												$p_s \times 10^5$	
−125	0.9887	8.411	.000	8.411	−30.057	.000	−30.057	−0.07634	.00000	−0.07634	−210.28	−0.4538	0.4710	−125
−120	1.606	8.537	.000	8.537	−28.852	.000	−28.852	−0.07277	.00000	−0.07277	−208.52	−0.4485	.7653	−120
−115	2.571	8.664	.000	8.664	−27.648	.000	−27.648	−0.06924	.00000	−0.06924	−206.73	−0.4433	1.226	−115
−110	4.063	8.792	.000	8.792	−26.444	.000	−26.444	−0.06577	.00000	−0.06577	−204.92	−0.4381	1.939	−110
−105	6.340	8.919	.000	8.919	−25.240	.001	−25.239	−0.06234	.00000	−0.06234	−203.09	−0.4329	3.026	−105
−100	9.772	9.046	.000	9.046	−24.037	.001	−24.036	−0.05897	.00000	−0.05897	−201.23	−0.4277	4.666	−100
	$H_s \times 10^6$												$p_s \times 10^4$	
−95	1.489	9.173	.000	9.173	−22.835	.002	−22.833	−0.05565	.00000	−0.05565	−199.35	−0.4225	0.7111	−95
−90	2.242	9.300	.000	9.300	−21.631	.002	−21.629	−0.05237	.00001	−0.05236	−197.44	−0.4173	1.071	−90
−85	3.342	9.426	.000	9.426	−20.428	.003	−20.425	−0.04913	.00001	−0.04912	−195.51	−0.4121	1.597	−85
−80	4.930	9.553	.000	9.553	−19.225	.005	−19.220	−0.04595	.00001	−0.04594	−193.55	−0.4069	2.356	−80
−75	7.196	9.680	.000	9.680	−18.022	.007	−18.015	−0.04280	.00002	−0.04278	−191.57	−0.4017	3.441	−75
−70	10.40	9.806	.000	9.806	−16.820	.011	−16.809	−0.03969	.00003	−0.03966	−189.56	−0.3965	4.976	−70
−65	14.91	9.932	.000	9.932	−15.617	.015	−15.602	−0.03663	.00005	−0.03658	−187.53	−0.3913	7.130	−65
	$H_s \times 10^5$												$p_s \times 10^3$	
−60	2.118	10.059	.000	10.059	−14.416	.022	−14.394	−0.03360	.00006	−0.03354	−185.47	−0.3861	1.0127	−60
−55	2.982	10.186	.000	10.186	−13.214	.031	−13.183	−0.03061	.00009	−0.03052	−183.39	−0.3810	1.4258	−55
−50	4.163	10.313	.001	10.314	−12.012	.043	−11.969	−0.02766	.00012	−0.02754	−181.29	−0.3758	1.9910	−50
−45	5.766	10.440	.001	10.441	−10.811	.060	−10.751	−0.02474	.00015	−0.02459	−179.16	−0.3707	2.7578	−45
−40	7.925	10.566	.001	10.567	−9.609	.083	−9.526	−0.02186	.00021	−0.02165	−177.01	−0.3655	3.7906	−40
−35	10.81	10.693	.002	10.695	−8.408	.113	−8.295	−0.01902	.00028	−0.01874	−174.84	−0.3604	5.1713	−35
	$H_s \times 10^4$												$p_s \times 10^2$	
−30	1.464	10.820	.002	10.822	−7.207	.154	−7.053	−0.01621	.00038	−0.01583	−172.64	−0.3552	0.70046	−30
−25	1.969	10.946	.004	10.950	−6.005	.207	−5.798	−0.01342	.00051	−0.01291	−170.42	−0.3500	.94212	−25
−20	2.630	11.073	.005	11.078	−4.804	.277	−4.527	−0.01067	.00068	−0.00999	−168.17	−0.3449	1.2587	−20
−15	3.491	11.200	.006	11.206	−3.603	.368	−3.235	−0.00796	.00089	−0.00707	−165.90	−0.3398	1.6706	−15
−10	4.606	11.326	.008	11.334	−2.402	.487	−1.915	−0.00529	.00115	−0.00414	−163.60	−0.3346	2.2035	−10
−5	6.040	11.452	.011	11.463	−1.201	.639	−0.562	−0.00263	.00149	−0.00114	−161.28	−0.3295	2.8886	−5
	$H_s \times 10^3$													
0	0.7872	11.578	.015	11.593	0.000	.835	0.835	0.00000	.00192	0.00192	−158.93	−0.3244	3.7645	0
5	1.020	11.705	.019	11.724	1.201	1.085	2.286	.00260	.00246	.00506	−156.57	−0.3193	4.8779	5
10	1.315	11.831	.025	11.856	2.402	1.401	3.803	.00518	.00314	.00832	−154.17	−0.3141	6.2858	10
15	1.687	11.958	.032	11.990	3.603	1.800	5.403	.00772	.00399	.01171	−151.76	−0.3090	8.0565	15
20	2.152	12.084	.042	12.126	4.804	2.302	7.106	.01023	.00504	.01527	−149.31	−0.3039	10.272	20
25	2.733	12.211	.054	12.265	6.005	2.929	8.934	.01273	.00635	.01908	−146.85	−0.2988	13.032	25
30	3.454	12.338	.068	12.406	7.206	3.709	10.915	.01519	.00796	.02315	−144.36	−0.2936	16.452	30
32	3.788	12.388	.075	12.463	7.686	4.072	11.758	.01617	.00870	.02487	−143.36	−0.2916	18.035	32
32*	3.788	12.388	.075	12.463	7.686	4.072	11.758	.01617	.00870	.02487	0.04	0.0000	18.037	32*
34	4.107	12.438	.082	12.520	8.167	4.418	12.585	.01715	.00940	.02655	2.06	.0041	19.546	34
													p_s	
36	4.450	12.489	.089	12.578	8.647	4.791	13.438	.01812	.01016	.02828	4.07	.0081	0.21166	36
38	4.818	12.540	.097	12.637	9.128	5.191	14.319	.01909	.01097	.03006	6.08	.0122	.22904	38
40	5.213	12.590	.105	12.695	9.608	5.622	15.230	.02005	.01183	.03188	8.09	.0162	.24767	40
42	5.638	12.641	.114	12.755	10.088	6.084	16.172	.02101	.01275	.03376	10.09	.0202	.26763	42
44	6.091	12.691	.124	12.815	10.569	6.580	17.149	.02197	.01373	.03570	12.10	.0242	.28899	44

NOTE: Compiled by John A. Goff and S. Gratch. See also Keenan and Kaye. *Thermodynamic Properties of Air,* Wiley, New York, 1945. Enthalpy of dry air taken as zero at 0°F. Enthalpy of liquid water taken as zero at 32°F.

To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

*Extrapolated to represent metastable equilibrium with undercooled liquid.

TABLE 12-1 Thermodynamic Properties of Moist Air (Standard Atmospheric Pressure, 29.921 inHg) *(Continued)*

Temp. t, °F.	Saturation humidity $H_s \times 10^3$	Volume, cu. ft./lb. dry air			Enthalpy, B.t.u./lb. dry air			Entropy, B.t.u./(°F.)(lb. dry air)			Condensed water			Temp. t, °F.
		v_a	v_{as}	v_s	h_a	h_{as}	h_s	s_a	s_{as}	s_s	Enthalpy, B.t.u./lb. h_w	Entropy, B.t.u./(lb.)(°F.) s_w	Vapor press., in. Hg $p_s \times 10^6$	
46	6.578	12.742	.134	12.876	11.049	7.112	18.161	.02293	.01478	.03771	14.10	.0282	.31185	46
48	7.100	12.792	.146	12.938	11.530	7.681	19.211	.02387	.01591	.03978	16.11	.0321	.33629	48
50	7.658	12.843	.158	13.001	12.010	8.291	20.301	.02481	.01711	.04192	18.11	.0361	.36240	50
52	8.256	12.894	.170	13.064	12.491	8.945	21.436	.02575	.01839	.04414	20.11	.0400	.39028	52
54	8.894	12.944	.185	13.129	12.971	9.644	22.615	.02669	.01976	.04645	22.12	.0439	.42004	54
56	9.575	12.995	.200	13.195	13.452	10.39	23.84	.02762	.02121	.04883	24.12	.0478	.45176	56
58	10.30	13.045	.216	13.261	13.932	11.19	25.12	.02855	.02276	.05131	26.12	.0517	.48558	58
60	11.08	13.096	.233	13.329	14.413	12.05	26.46	.02948	.02441	.05389	28.12	.0555	.52159	60
62	11.91	13.147	.251	13.398	14.893	12.96	27.85	.03040	.02616	.05656	30.12	.0594	.55994	62
64	12.80	13.197	.271	13.468	15.374	13.94	29.31	.03132	.02803	.05935	32.12	.0632	.60073	64
66	13.74	13.247	.292	13.539	15.855	14.98	30.83	.03223	.03002	.06225	34.11	.0670	.64411	66
68	14.75	13.298	.315	13.613	16.335	16.09	32.42	.03314	.03213	.06527	36.11	.0708	.69019	68
	$H_s \times 10^2$													
70	1.582	13.348	.339	13.687	16.816	17.27	34.09	.03405	.03437	.06842	38.11	.0746	.73915	70
72	1.697	13.398	.364	13.762	17.297	18.53	35.83	.03495	.03675	.07170	40.11	.0784	.79112	72
74	1.819	13.449	.392	13.841	17.778	19.88	37.66	.03585	.03928	.07513	42.10	.0821	.84624	74
76	1.948	13.499	.422	13.921	18.259	21.31	39.57	.03675	.04197	.07872	44.10	.0859	.90470	76
78	2.086	13.550	.453	14.003	18.740	22.84	41.58	.03765	.04482	.08247	46.10	.0896	.96665	78
80	2.233	13.601	0.486	14.087	19.221	24.47	43.69	0.03854	0.04784	0.08638	48.10	0.0933	1.0323	80
82	2.389	13.651	.523	14.174	19.702	26.20	45.90	.03943	.05105	.09048	50.09	.0970	1.1017	82
84	2.555	13.702	.560	14.262	20.183	28.04	48.22	.04031	.05446	.09477	52.09	.1007	1.1752	84
86	2.731	13.752	.602	14.354	20.663	30.00	50.66	.04119	.05807	.09926	54.08	.1043	1.2529	86
88	2.919	13.803	.645	14.448	21.144	32.09	53.23	.04207	.06189	.10396	56.08	.1080	1.3351	88
90	3.118	13.853	.692	14.545	21.625	34.31	55.93	.04295	.06596	.10890	58.08	.1116	1.4219	90
92	3.330	13.904	.741	14.645	22.106	36.67	58.78	.04382	.07025	.11407	60.07	.1153	1.5135	92
94	3.556	13.954	.795	14.749	22.587	39.18	61.77	.04469	.07480	.11949	62.07	.1188	1.6102	94
96	3.795	14.005	.851	14.856	23.068	41.85	64.92	.04556	.07963	.12519	64.06	.1224	1.7123	96
98	4.049	14.056	.911	14.967	23.548	44.68	68.23	.04643	.08474	.13117	66.06	.1260	1.8199	98
100	4.319	14.106	.975	15.081	24.029	47.70	71.73	.04729	.09016	.13745	68.06	.1296	1.9333	100
102	4.606	14.157	1.043	15.200	24.510	50.91	75.42	.04815	.09591	.14406	70.05	.1332	2.0528	102
104	4.911	14.207	1.117	15.324	24.991	54.32	79.31	.04900	.1020	.1510	72.05	.1367	2.1786	104
	$H_s \times 10$													
106	0.5234	14.258	1.194	15.452	25.472	57.95	83.42	.04985	.1085	.1584	74.04	.1403	2.3109	106
108	.5578	14.308	1.278	15.586	25.953	61.80	87.76	.05070	.1153	.1660	76.04	.1438	2.4502	108
110	.5944	14.359	1.365	15.724	26.434	65.91	92.34	.05155	.1226	.1742	78.03	.1472	2.5966	110
112	.6333	14.409	1.460	15.869	26.915	70.27	97.18	.05239	.1302	.1826	80.03	.1508	2.7505	112
114	.6746	14.460	1.560	16.020	27.397	74.91	102.31	.05323	.1384	.1916	82.03	.1543	2.9123	114
116	.7185	14.510	1.668	16.178	27.878	79.85	107.73	.05407	.1470	.2011	84.02	.1577	3.0821	116
118	.7652	14.561	1.782	16.343	28.359	85.10	113.46	.05490	.1562	.2111	86.02	.1612	3.2603	118
120	.8149	14.611	1.905	16.516	28.841	90.70	119.54	.05573	.1659	.2216	88.01	.1646	3.4474	120
122	.8678	14.662	2.034	16.696	29.322	96.66	125.98	.05656	.1763	.2329	90.01	.1681	3.6436	122
124	.9242	14.712	2.174	16.886	29.804	103.0	132.8	.05739	.1872	.2446	92.01	.1715	3.8493	124
126	.9841	14.763	2.323	17.086	30.285	109.8	140.1	.05821	.1989	.2571	94.01	.1749	4.0649	126
128	1.048	14.813	2.482	17.295	30.766	117.0	147.8	.05903	.2113	.2703	96.00	.1783	4.2907	128
130	1.116	14.864	2.652	17.516	31.248	124.7	155.9	.05985	.2245	.2844	98.00	.1817	4.5272	130
132	1.189	14.915	2.834	17.749	31.729	133.0	164.7	.06067	.2386	.2993	100.00	.1851	4.7747	132
134	1.267	14.965	3.029	17.994	32.211	141.8	174.0	.06148	.2536	.3151	102.00	.1885	5.0337	134
136	1.350	15.016	3.237	18.253	32.692	151.2	183.9	.06229	.2695	.3318	104.00	.1918	5.3046	136
138	1.439	15.066	3.462	18.528	33.174	161.2	194.4	.06310	.2865	.3496	106.00	.1952	5.5878	138
	H_s													
140	0.1534	15.117	3.702	18.819	33.655	172.0	205.7	.06390	.3047	.3686	107.99	.1985	5.8838	140
142	.1636	15.167	3.961	19.128	34.136	183.6	217.7	.06470	.3241	.3888	109.99	.2018	6.1930	142
144	.1745	15.218	4.239	19.457	34.618	196.0	230.6	.06549	.3449	.4104	111.99	.2051	6.5160	144
146	.1862	15.268	4.539	19.807	35.099	209.3	244.4	.06629	.3672	.4335	113.99	.2084	6.8532	146
148	.1989	15.319	4.862	20.181	35.581	223.7	259.3	.06708	.3912	.4583	115.99	.2117	7.2051	148
150	.2125	15.369	5.211	20.580	36.063	239.2	275.3	.06787	.4169	.4848	117.99	.2150	7.5722	150
152	.2271	15.420	5.587	21.007	36.545	255.9	292.4	.06866	.4445	.5132	119.99	.2183	7.9550	152
154	.2430	15.470	5.996	21.466	37.026	273.9	310.9	.06945	.4743	.5438	121.99	.2216	8.3541	154
156	.2602	15.521	6.439	21.960	37.508	293.5	331.0	.07023	.5066	.5768	123.99	.2248	8.7701	156
158	.2788	15.571	6.922	22.493	37.990	314.7	352.7	.07101	.5415	.6125	125.99	.2281	9.2036	158

TABLE 12-1 Thermodynamic Properties of Moist Air (Standard Atmospheric Pressure, 29.921 inHg) *(Concluded)*

Temp. t, °F.	Saturation humidity $H_s \times 10^8$	Volume, cu. ft./lb. dry air			Enthalpy, B.t.u./lb. dry air			Entropy, B.t.u./(°F.)(lb. dry air)			Condensed water Enthalpy, B.t.u./lb.	Condensed water Entropy, B.t.u./(lb.)(°F.)	Condensed water Vapor press., in. Hg	Temp. t, °F.
		v_a	v_{as}	v_s	h_a	h_{as}	h_s	s_a	s_{as}	s_s	h_w	s_w	$p_s \times 10^6$	
160	.2990	15.622	7.446	23.068	38.472	337.8	376.3	.07179	.5793	.6511	128.00	.2313	9.6556	160
162	.3211	15.672	8.020	23.692	38.954	363.0	402.0	.07257	.6204	.6930	130.00	.2345	10.125	162
164	.3452	15.723	8.648	24.371	39.436	390.5	429.9	.07334	.6652	.7385	132.00	.2377	10.614	164
166	.3716	15.773	9.339	25.112	39.918	420.8	460.7	.07411	.7142	.7883	134.00	.2409	11.123	166
168	.4007	15.824	10.098	25.922	40.400	454.0	494.4	.07488	.7680	.8429	136.01	.2441	11.652	168
170	.4327	15.874	10.938	26.812	40.882	490.6	531.5	.07565	.8273	.9030	138.01	.2473	12.203	170
172	.4682	15.925	11.870	27.795	41.364	531.3	572.7	.07641	.8927	.9691	140.01	.2505	12.775	172
174	.5078	15.975	12.911	28.886	41.846	576.5	618.3	.07718	.9654	1.0426	142.02	.2537	13.369	174
176	.5519	16.026	14.074	30.100	42.328	627.1	669.4	.07794	1.047	1.125	144.02	.2568	13.987	176
178	.6016	16.076	15.386	31.462	42.810	684.1	726.9	.07870	1.137	1.216	146.03	.2600	14.628	178
180	.6578	16.127	16.870	32.997	43.292	748.5	791.8	.07946	1.240	1.319	148.03	.2631	15.294	180
182	.7218	16.177	18.565	34.742	43.775	821.9	865.7	.08021	1.357	1.437	150.04	.2662	15.985	182
184	.7953	16.228	20.513	36.741	44.257	906.2	950.5	.08096	1.490	1.571	152.04	.2693	16.702	184
186	.8805	16.278	22.775	39.053	44.740	1004	1049	.08171	1.645	1.727	154.05	.2724	17.446	186
188	.9802	16.329	25.427	41.756	45.222	1119	1164	.08245	1.825	1.907	156.06	.2755	18.217	188
190	1.099	16.379	28.580	44.959	45.704	1255	1301	.08320	2.039	2.122	158.07	.2786	19.017	190
192	1.241	16.430	32.375	48.805	46.187	1418	1464	.08394	2.296	2.380	160.07	.2817	19.845	192
194	1.416	16.480	37.036	53.516	46.670	1619	1666	.08468	2.609	2.694	162.08	.2848	20.704	194
196	1.635	16.531	42.885	59.416	47.153	1871	1918	.08542	3.002	3.087	164.09	.2879	21.594	196
198	1.917	16.581	50.426	67.007	47.636	2195	2243	.08616	3.507	3.593	166.10	.2910	22.514	198
200	2.295	16.632	60.510	77.142	48.119	2629	2677	.08689	4.179	4.266	168.11	.2940	23.468	200

TABLE 12-2 Additive Corrections for *H*, *h*, and *v* When Barometric Pressure Differs from Standard Barometer

Wet-bulb temp. t_w	Sat. vapor press., in. Hg	Approximate altitude in feet													
		−900		900		1800		2700		3700		4800		5900	
		$\Delta p = +1$		$\Delta p = -1$		$\Delta p = -2$		$\Delta p = -3$		$\Delta p = -4$		$\Delta p = -5$		$\Delta p = -6$	
		ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh
−10	0.022	−0.10	−0.02	0.11	0.02	0.23	0.03	0.36	0.05	0.50	0.07	0.64	0.10	0.81	0.12
−8	.025	−0.12	−0.02	.12	.02	.26	.04	.40	.06	.55	.08	.72	.11	.90	.13
−6	.027	−0.13	−0.02	.14	.02	.29	.04	.44	.07	.62	.09	.80	.12	1.00	.15
−4	.030	−0.14	0.02	.15	.02	.32	.05	.50	.07	.69	.10	.89	.13	1.12	.17
−2	.034	−0.16	−0.02	.17	.02	.35	.05	.55	.08	.76	.11	.99	.15	1.24	.19
0	.038	−0.18	−0.03	.19	.03	.39	.06	.61	.09	.85	.13	1.10	.17	1.38	.21
2	.042	−0.20	−0.03	.21	.03	.44	.07	.68	.10	.94	.14	1.22	.19	1.53	.23
4	.046	−0.22	−0.03	.23	.03	.48	.07	.75	.11	1.05	.16	1.36	.21	1.70	.26
6	.051	−0.24	−0.04	.26	.04	.54	.08	.83	.13	1.16	.18	1.51	.23	1.89	.29
8	.057	−0.27	−0.04	.29	.04	.59	.09	.93	.14	1.28	.19	1.67	.25	2.09	.32
10	.063	−0.30	−0.04	.32	.05	.66	.10	1.03	.16	1.42	.22	1.85	.28	2.31	.35
12	.069	−0.33	−0.05	.35	.05	.73	.11	1.13	.17	1.57	.24	2.04	.31	2.56	.39
14	.077	−0.36	−0.05	.39	.06	.81	.12	1.25	.19	1.74	.26	2.26	.34	2.82	.43
16	.085	−0.40	−0.06	.43	.06	.89	.14	1.38	.21	1.92	.29	2.49	.38	3.12	.48
18	.093	−0.44	−0.07	.47	.07	.98	.15	1.53	.23	2.12	.32	2.75	.42	3.44	.53
20	.103	−0.49	−0.08	.52	.08	1.08	.17	1.68	.26	2.33	.36	3.03	.46	3.79	.58
22	.113	−0.5	−0.08	.6	.09	1.2	.18	1.9	.29	2.6	.40	3.4	.52	4.2	.64
24	.124	−0.6	−0.09	.6	.10	1.3	.20	2.1	.32	2.8	.43	3.7	.57	4.6	.71
26	.137	−0.7	−0.10	.7	.11	1.4	.22	2.3	.35	3.1	.48	4.1	.63	5.1	.78
28	.150	−0.7	−0.11	.8	.12	1.6	.24	2.5	.38	3.4	.52	4.5	.69	5.6	.86
30	.165	−0.8	−0.12	.8	.13	1.7	.27	2.7	.42	3.8	.58	4.9	.75	6.1	.92
32	.180	−0.9	−0.13	.9	.14	1.9	.29	3.0	.45	4.1	.63	5.3	.82	6.6	1.01
34	.197	−0.9	−0.14	1.0	.15	2.1	.32	3.2	.49	4.4	.68	5.7	.88	7.2	1.11
36	.212	−1.0	−0.15	1.1	.17	2.2	.35	3.5	.53	4.8	.74	6.2	.96	7.8	1.20
38	.229	−1.1	−0.17	1.2	.18	2.4	.37	3.8	.58	5.2	.80	6.8	1.05	8.4	1.30
40	.248	−1.2	−0.18	1.3	.20	2.6	.41	4.1	.63	5.7	.88	7.4	1.14	9.2	1.42
42	.268	−1.3	−0.20	1.4	.21	2.8	.44	4.4	.69	6.1	.94	8.0	1.23	10.0	1.54
44	.289	−1.4	−0.22	1.5	.23	3.1	.47	4.8	.74	6.7	1.04	8.7	1.34	10.8	1.67
46	.312	−1.5	−0.23	1.6	.25	3.3	.51	5.2	.80	7.2	1.11	9.4	1.45	11.7	1.81
48	.336	−1.6	−0.25	1.8	.27	3.6	.56	5.6	.87	7.8	1.21	10.2	1.58	12.6	1.95
50	.3624	−1.7	−0.27	1.9	.29	3.9	.60	6.1	.94	8.4	1.30	10.9	1.69	13.6	2.11
52	.3903	−1.9	−0.29	2.0	.32	4.2	.65	6.5	1.01	9.0	1.40	11.8	1.83	14.7	2.28
54	.4200	−2.0	−0.31	2.2	.34	4.5	.70	7.0	1.09	9.7	1.50	12.7	1.97	15.8	2.45
56	.4518	−2.2	−0.34	2.4	.37	4.9	.76	7.6	1.18	10.5	1.63	13.7	2.13	17.1	2.66
58	.4856	−2.3	−0.37	2.5	.39	5.3	.82	8.2	1.27	11.3	1.76	14.7	2.28	18.4	2.86

TABLE 12-2 Additive Corrections for *H*, *h*, and *v* When Barometric Pressure Differs from Standard Barometer (*Concluded*)

Approximate altitude in feet

Wet-bulb temp. t_w	Sat. vapor press., in. Hg	−900		900		1800		2700		3700		4800		5900	
		$\Delta p = +1$		$\Delta p = -1$		$\Delta p = -2$		$\Delta p = -3$		$\Delta p = -4$		$\Delta p = -5$		$\Delta p = -6$	
		ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh	ΔH_s	Δh
60	.522	−2.5	−0.40	2.7	.42	5.7	.88	8.8	1.37	12.2	1.90	15.9	2.47	19.9	3.09
62	.560	−2.7	−0.43	2.9	.46	6.1	.95	9.5	1.48	13.2	2.05	17.1	2.66	21.4	3.33
64	.601	−2.9	−0.46	3.2	.49	6.5	1.02	10.2	1.59	14.2	2.21	18.4	2.87	23.1	3.60
66	.644	−3.2	−0.50	3.4	.53	7.1	1.10	11.0	1.72	15.3	2.38	19.8	3.09	24.8	3.87
68	.690	−3.4	−0.53	3.7	.57	7.6	1.18	11.8	1.84	16.4	2.56	21.3	3.32	26.7	4.16
70	.739	−3.7	−0.57	3.9	.61	8.1	1.27	12.7	1.98	17.6	2.75	22.9	3.58	28.7	4.48
72	.791	−3.9	−0.61	4.2	.66	8.7	1.36	13.6	2.13	18.8	2.94	24.6	3.84	30.9	4.82
74	.846	−4.2	−0.66	4.6	.71	9.4	1.46	14.6	2.28	20.2	3.16	26.4	4.14	33.1	5.18
76	.905	−4.5	−0.71	4.9	.77	10.0	1.57	15.7	2.46	21.7	3.39	28.3	4.42	35.5	5.56
78	.967	−4.9	−0.76	5.2	.82	10.8	1.69	16.9	2.65	23.3	3.65	30.5	4.77	38.2	5.98
80	1.032	−5.2	−0.82	5.6	.88	11.6	1.82	18.1	2.84	25.1	3.93	32.7	5.13	41.0	6.43
82	1.102	−5.6	−0.88	6.0	.94	12.5	1.96	19.5	3.06	27.0	4.24	35.1	5.51	44.0	6.90
84	1.175	−6.0	−0.94	6.4	1.00	13.3	2.10	20.9	3.28	28.9	4.54	37.7	5.92	47.2	7.41
86	1.253	−6.4	−1.00	6.9	1.08	14.3	2.24	22.3	3.50	30.9	4.85	40.4	6.34	50.6	7.94
88	1.335	−6.9	−1.08	7.4	1.16	15.3	2.40	23.9	3.75	33.1	5.20	43.2	6.79	54.2	8.51
90	1.422	−7.4	−1.16	7.9	1.24	16.5	2.59	25.7	4.04	35.6	5.60	46.4	7.29	58.2	9.15
92	1.514	−7.9	−1.24	8.5	1.34	17.6	2.77	27.5	4.33	38.2	6.01	49.8	7.83	62.5	9.83
94	1.610	−8.5	−1.34	9.1	1.43	18.9	2.98	29.5	4.64	41.0	6.46	53.4	8.41	67.0	10.55
96	1.712	−9.1	−1.43	9.8	1.54	20.2	3.18	31.5	4.96	43.8	6.90	57.2	9.01	71.7	11.30
98	1.820	−9.7	−1.53	10.4	1.64	21.7	3.42	33.8	5.33	47.0	7.41	61.3	9.67	76.8	12.11
100	1.933	−10.4	−1.64	11.2	1.77	23.2	3.66	36.3	5.73	50.4	7.95	65.7	10.37	82.5	13.02
102	2.053	−11.1	−1.75	12.0	1.90	24.8	3.92	38.9	6.14	54.1	8.54	70.5	11.13	88.5	13.98
104	2.179	−11.9	−1.88	12.8	2.02	26.6	4.20	41.6	6.58	57.9	9.15	75.5	11.93	94.8	14.98
106	2.311	−12.8	−2.02	13.7	2.17	28.6	4.52	44.6	7.06	62.1	9.82	81.1	12.83	101.7	16.09
108	2.450	−13.7	−2.17	14.7	2.33	30.6	4.84	47.7	7.55	66.5	10.53	87.0	13.77	109.1	17.27
110	2.597	−14.7	−2.33	15.8	2.50	32.8	5.20	51.3	8.13	71.3	11.30	93.1	14.75	117.0	18.54
112	2.751	−15.7	−2.49	16.9	2.68	35.2	5.58	55.0	8.72	76.4	12.11	99.9	15.84	125.9	19.96
114	2.913	−16.9	−2.68	18.1	2.87	37.7	5.98	58.9	9.50	82.0	13.01	107.3	17.03	135.0	21.42
116	3.082	−18.0	−2.86	19.4	3.08	40.4	6.42	63.2	10.03	88.0	13.97	115.1	18.28	144.7	22.98
118	3.260	−19.3	−3.07	20.8	3.31	43.3	6.88	67.8	10.77	94.4	15.00	123.5	19.63	155.4	24.73
120	3.448	−20.7	−3.29	22.4	3.56	46.6	7.41	72.8	11.58	101.4	16.13	132.7	21.10	167.1	26.58
122	3.644	−22.2	−3.53	24.0	3.82	50.0	7.96	78.2	12.45	109.0	17.35	142.6	22.70	179.6	28.58
124	3.850	−23.8	−3.79	25.8	4.11	53.7	8.55	84.0	13.38	117.1	18.65	153.3	24.42	193.2	30.77
126	4.065	−25.6	−4.08	27.6	4.40	57.7	9.20	90.3	14.39	125.9	20.07	165.0	26.30	208.0	33.15
128	4.291	−27.5	−4.39	29.7	4.74	62.0	9.89	97.1	15.49	135.5	21.61	177.6	28.33	224.0	35.73
130	4.527	−29.5	−4.71	32.0	5.11	66.7	10.64	104.5	16.68	145.9	23.29	191.4	30.55	241.5	38.55
132	4.775	−31.8	−5.08	34.4	5.50	71.8	11.47	112.6	17.99	157.2	25.11	206.3	32.96	260.6	41.63
134	5.034	−34.2	−5.47	37.1	5.93	77.4	12.37	121.4	19.41	169.6	27.12	222.7	35.60	281.4	44.99
136	5.305	−36.8	−5.89	40.0	6.40	83.4	13.34	130.9	20.94	183.1	29.30	240.5	38.48	304.2	48.67
138	5.588	−39.7	−6.36	43.2	6.92	90.0	14.41	141.4	22.64	197.8	31.67	260.1	41.65	329.3	52.73
140	5.884	−42.8	−6.86	46.5	8.45	97.3	15.59	152.8	24.48	214.0	34.29	281.6	45.12	356.8	57.17

t = dry-bulb temperature, °F
t_w = wet-bulb temperature, °F
p = barometric pressure, inHg
Δp = pressure difference from standard barometer (inHg)
H = moisture content of air, gr/lb dry air
H_s = moisture content of air saturated at wet-bulb temperature (t_w), gr/lb dry air
ΔH = moisture-content correction of air when barometric pressure differs from standard barometer, gr/lb dry air
ΔH_s = moisture-content correction of air saturated at wet-bulb temperature when barometric pressure differs from standard barometer, gr/lb dry air
NOTE: To obtain ΔH reduce value of ΔH_s by 1 percent where $t - t_w = 24$°F and correct proportionally when $t - t_w$ is not 24°F.
h = enthalpy of moist air, Btu/lb dry air
Δh = enthalpy correction when barometric pressure differs from standard barometer, for saturated or unsaturated air, Btu/lb dry air
v = volume of moist air, ft³/lb dry air

$$= \frac{0.754(t + 459.8)}{p}\left(1 + \frac{H}{4360}\right)$$

Example At a barometric pressure of 25.92 with 220°F dry-bulb and 100°F wet-bulb temperatures, determine H, h, and v. $\Delta p = -4$, and from table $\Delta H_s = 50.4$. From note,

$$\Delta H = \Delta H_s - \left(\frac{120}{24} \times 0.01 \times 50.4\right) = 50.4 - 2.5 = 47.9$$

Therefore $H = 102$ (from chart) $+ 47.9 = 149.9$ gr/lb. dry air. From table $\Delta h = 7.95$. Therefore, h = saturation enthalpy from chart + deviation + 7.95 = 71.7 − 2.0 + 7.95 = 77.65 Btu/lb dry air. From previous equation

$$v = \frac{0.754(220 + 459.7)}{25.92}\left(1 + \frac{149.9}{4360}\right) = 20.43 \text{ ft}^3\text{/lb dry air}$$

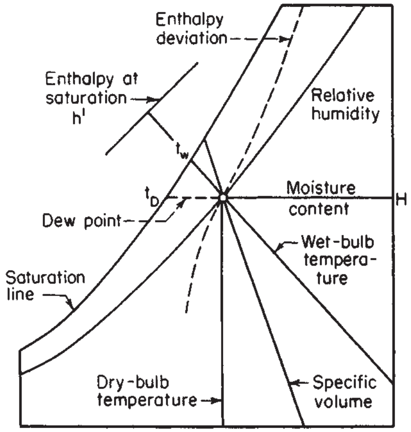

FIG. 12-6 Diagram of psychrometric chart showing the properties of moist air.

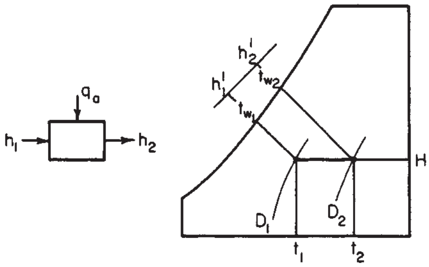

FIG. 12-7 Heating process.

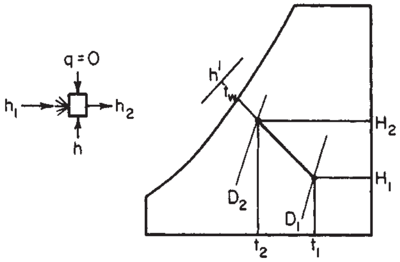

FIG. 12-8 Spray or evaporative cooling.

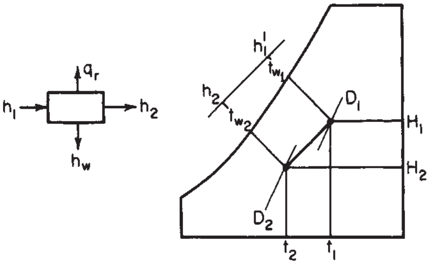

FIG. 12-9 Cooling and dehumidifying process.

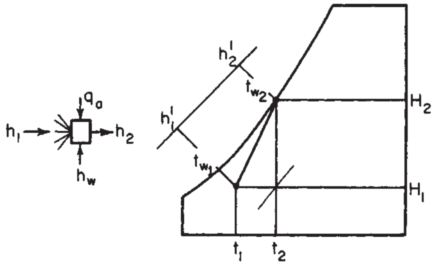

FIG. 12-10 Cooling tower.

Example 6: Cooling Tower (Continued)

Exit moisture $H_2 = 416$ gr/lb dry air

Inlet moisture $H_1 = 78$ gr/lb dry air

Moisture added $\Delta H = 338$ gr/lb dry air

Enthalpy of added moisture $h_w = 2.1$ Btu/lb dry air (from small diagram of Fig. 12-3)

If greater precision is desired, h_w can be calculated as

$$h_w = (338/7000)(1)(75 - 32)$$
$$= 2.08 \text{ Btu/lb dry air}$$

$$\text{Enthalpy of inlet air } h_1 = h'_1 + D_1 = 34.1 - 0.18$$
$$= 33.92 \text{ Btu/lb dry air}$$

$$\text{Enthalpy of exit air } h_2 = h'_2 + D_2 = 92.34 + 0$$
$$= 92.34 \text{ Btu/lb dry air}$$

$$\text{Heat dissipated} = h_2 - h_1 - h_w$$
$$= 92.34 - 33.92 - 2.08$$
$$= 56.34 \text{ Btu/lb dry air}$$

$$\text{Specific volume of inlet air} = 14.1 \text{ ft}^3\text{/lb dry air}$$

$$\text{Total heat dissipated} = \frac{(1000)(56.34)}{14.1} = 3990 \text{ Btu/min}$$

Example 7: Recirculating Dryer A dryer is removing 100 lb water/h from the material being dried. The air entering the dryer has a dry-bulb temperature of 180°F and a wet-bulb temperature of 110°F. The air leaves the dryer at 140°F. A portion of the air is recirculated after mixing with room air having a dry-bulb temperature of 75°F and a relative humidity of 60 percent. Determine quantity of air required, recirculation rate, and load on the preheater if it is assumed that the system is adiabatic. Neglect heatup of the feed and of the conveying equipment.

Solution. The path followed is shown in Fig. 12-11.

Humidity of room air $H_1 = 0.0113$ lb/lb dry air

Humidity of air entering dryer $H_3 = 0.0418$ lb/lb dry air

Humidity of air leaving dryer $H_4 = 0.0518$ lb/lb dry air

$$\text{Enthalpy of room air } h_1 = 30.2 - 0.3$$
$$= 29.9 \text{ Btu/lb dry air}$$

$$\text{Enthalpy of entering air } h_3 = 92.5 - 1.3$$
$$= 91.2 \text{ Btu/lb dry air}$$

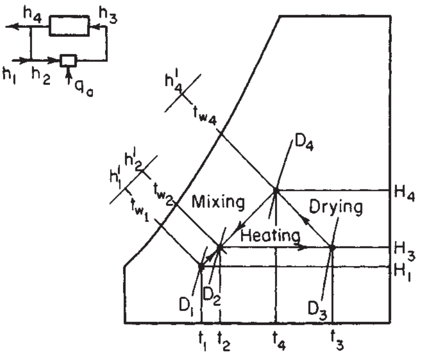

FIG. 12-11 Drying process with recirculation.

$$\begin{aligned}\text{Enthalpy of leaving air } h_4 &= 92.5 - 0.55\\ &= 91.95 \text{ Btu/lb dry air}\end{aligned}$$

Quantity of air required is 100/(0.0518 − 0.0418) = 10,000 lb dry air/h. At the dryer inlet the specific volume is 17.1 ft^3/lb dry air. Air volume is (10,000)(17.1)/60 = 2850 ft^3/min. Fraction exhausted is

$$\frac{X}{W_a} = \frac{0.0518 - 0.0418}{0.0518 - 0.0113} = 0.247$$

where X = quantity of fresh air and W_a = total air flow. Thus 75.3 percent of the air is recirculated. Load on the preheater is obtained from an enthalpy balance

$$\begin{aligned}q_a &= 10{,}000(91.2) - 2470(29.9) - 7530(91.95)\\ &= 146{,}000 \text{ Btu/h}\end{aligned}$$

Use of Psychrometric Charts at Pressures Other Than Atmospheric The psychrometric charts shown as Figs. 12-1 through 12-4 and the data of Table 12-1 are based on a system pressure of 1 atm (29.92 inHg). For other system pressures, these data must be corrected for the effect of pressure. Additive corrections to be applied to the atmospheric values of absolute humidity and enthalpy are given in Table 12-2.

The **specific volume** of moist air in cubic feet per pound of dry air can be determined for other pressures, if ideal-gas behavior is assumed, by the following equation:

$$v = \frac{0.754(t + 460)}{P}\left(1 + \frac{HM_a}{M_w}\right) \tag{12-5}$$

where v = specific volume, ft^3/lb dry air; t = dry-bulb temperature, °F; P = pressure, inHg; H = absolute humidity, lb water/lb dry air; M_a = molecular weight of air, lb/(lb·mol); and M_w = molecular weight of water vapor, lb/(lb·mol).

Relative humidity and **dew point** can be determined for other than atmospheric pressure from the partial pressure of water in the mixture and from the vapor pressure of water vapor. The partial pressure of water is calculated, if ideal-gas behavior is assumed, as

$$p = \frac{HP}{(M_w/M_a) + H} \tag{12-6}$$

where p = partial pressure of water vapor, inHg; P = total pressure, inHg; H = absolute humidity, lb water/lb dry air, corrected to the actual pressure; M_a = molecular weight of air, lb/(lb·mol); and M_w = molecular weight of water vapor, lb/(lb·mol). The dew point of the mixture is then read directly from a table of vapor pressures as the temperature corresponding to the calculated partial pressure.

The relative humidity is obtained by dividing the calculated partial pressure by the vapor pressure of water at the dry-bulb temperature. Thus:

$$\text{Relative humidity} = 100p/p_s \tag{12-7}$$

where p = calculated partial pressure, inHg; and p_s = vapor pressure at dry-bulb temperature, inHg.

The preceding equations, which have assumed that both the air and the water vapor behave as ideal gases, are sufficiently accurate for most engineering calculations. If it is desired to remove the restriction that water vapor behave as an ideal gas, the actual density ratio should be used in place of the molecular-weight ratio in Eqs. (12-5) and (12-6).

Since the Schmidt number, Prandtl number, latent heat of vaporization, and humid heat are all essentially independent of pressure, the adiabatic-saturation-temperature and wet-bulb-temperature lines will be substantially equal at pressures different from atmospheric.

Example 8: Determination of Air Properties For a barometric pressure of 25.92 inHg ($\Delta p = -4$), a dry-bulb temperature of 90°F, and a wet-bulb temperature of 70°F determine the following: absolute humidity, enthalpy, dew point, relative humidity, and specific volume.

Solution. From Fig. 12-2, the moisture content is 78 gr/lb dry air = 0.0114 lb/lb dry air. From Table 12-2 at t_w = 70°F and $\Delta p = -4$ read ΔH_s = 17.6 gr/lb dry air (additive correction for air saturated at the wet-bulb temperature).

$\Delta H = 17.6[1 - (20/24)(0.01)] = 17.4$, or actual humidity is 78 + 17.4 = 95.4 gr/lb dry air, or 0.01362 lb/lb dry air. (See footnotes for Table 12-2.)

The enthalpy is obtained from Fig. 12-2 as $h = h' + D = 34.1 - 0.18 = 33.92$. To this must be added the correction of 2.75 read from Table 12-2 for $\Delta p = -4$ and t_w = 70°F, giving the true enthalpy as 33.92 + 2.75 = 36.67 Btu/lb dry air.

The partial pressure of water vapor is calculated from Eq. (12-6) as

$$p = \frac{HP}{(M_w/M_a) + H} = \frac{0.01362 \times 25.92}{0.622 + 0.01362} = 0.556 \text{ inHg}$$

From a table of vapor pressure, this corresponds to a dew point of 61.8°F.

Relative humidity is obtained from Eq. (12-7) as 100 p/p_s = (100 × 0.556)/1.422 = 39.1 percent.

The specific volume in cubic feet per pound of dry air is obtained from Eq. (12-5):

$$\begin{aligned}v &= \frac{0.754(t + 460)}{25.92}\left(1 + \frac{HM_a}{M_w}\right)\\ &= \frac{0.754(90 + 460)}{25.92}\left(1 + \frac{0.01362}{0.622}\right)\\ &= 16.35 \text{ ft}^3\text{/lb dry air}\end{aligned}$$

MEASUREMENT OF HUMIDITY

Dew-Point Method The dew point of wet air is measured directly by observing the temperature at which moisture begins to form on an artificially cooled polished surface. The polished surface is usually cooled by evaporation of a low-boiling solvent such as ether, by vaporization of a condensed permanent gas such as carbon dioxide or liquid air, or by a temperature-regulated stream of water.

Although the dew-point method may be considered a fundamental technique for determining humidity, several uncertainties occur in its use. It is not always possible to measure precisely the temperature of the polished surface or to eliminate gradients across the surface. It is also difficult to detect the appearance or disappearance of fog; the usual practice is to take the dew point as the average of the temperatures when fog first appears on cooling and disappears on heating.

Wet-Bulb Method Probably the most commonly used method for determining the humidity of a gas stream is the measurement of wet- and dry-bulb temperatures. The wet-bulb temperature is measured by contacting the air with a thermometer whose bulb is covered by a wick saturated with water. If the process is adiabatic, the thermometer bulb attains the wet-bulb temperature. When the wet- and dry-bulb temperatures are known, the humidity is readily obtained from charts such as Figs. 12-1 through 12-4. In order to obtain reliable information, care must be exercised to ensure that the wet-bulb thermometer remains wet and that radiation to the bulb is minimized. The latter is accomplished by making the relative velocity between wick and gas stream high [a velocity of 4.6 m/s (15 ft/s) is usually adequate for commonly used thermometers] or by the use of radiation shielding. Making sure that the wick remains wet is a mechanical problem, and the method used depends to a large extent on the particular arrangement. Again, as with the dew-point method, errors associated with the measurement of temperature can cause difficulty.

For measurement of atmospheric humidities the **sling psychrometer** is widely used. This is composed of a wet- and dry-bulb thermometer mounted in a sling which is whirled manually to give the desired gas velocity across the bulb. In the **Assmann psychrometer** the air is drawn past the bulbs by a motor-driven fan.

In addition to the mercury-in-glass thermometer, other temperature-sensing elements may be used for psychrometers. These include resistance thermometers, thermocouples, bimetal thermometers, and thermistors.

Mechanical Hygrometers Materials such as human hair, wood fiber, and plastics have been used to measure humidity. These methods rely on a change in dimension with humidity.

Electric hygrometers measure the electrical resistance of a film of moisture-absorbing materials exposed to the gas. A wide variety of sensing elements have been used.

The **gravimetric method** is accepted as the most accurate humidity-measuring technique. In this method a known quantity of gas is passed over a moisture-absorbing chemical such as phosphorus pentoxide, and the increase in weight is determined.

EVAPORATIVE COOLING*

General References: *ASHRAE Handbook and Product Directory: Equipment,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1983. *Counterflow Cooling Tower Performance,* Pritchard Corporation, Kansas City, Mo., 1957. Hensley, "Cooling Tower Energy," *Heat. Piping Air Cond.* (October 1981). Kelley and Swenson, *Chem. Eng. Prog.,* **52,** 263 (1956). McAdams, *Heat Transmission,* 3d ed., McGraw-Hill, New York, 1954, pp. 356–365. Merkel, Z. *Ver. Dtsch. Ing. Forsch.,* no. 275 (1925). *The Parallel Path Wet-Dry Cooling Tower,* Marley Co., Mission Woods, Kan., 1972. *Performance Curves,* Cooling Tower Institute, Houston, 1967. *Plume Abatement and Water Conservation with Wet-Dry Cooling Tower,* Marley Co., Mission Woods, Kan., 1973. Tech. Bull. R-54-P-5, R-58-P-5, Marley Co., Mission Woods, Kan., 1957. Wood and Betts, *Engineer,* **189** (4912), 377, (4913), 349 (1950). Zivi and Brand, *Refrig. Eng.,* **64,** 8, 31–34, 90 (1956).

PRINCIPLES

The processes of cooling water are among the oldest known. Usually water is cooled by exposing its surface to air. Some of the processes are slow, such as the cooling of water on the surface of a pond; others are comparatively fast, such as the spraying of water into air. These processes all involve the exposure of water surface to air in varying degrees.

The heat-transfer process involves (1) latent heat transfer owing to vaporization of a small portion of the water and (2) sensible heat transfer owing to the difference in temperature of water and air. Approximately 80 percent of this heat transfer is due to latent heat and 20 percent to sensible heat.

Theoretical possible heat removal per pound of air circulated in a cooling tower depends on the temperature and moisture content of air. An indication of the moisture content of the air is its wet-bulb temperature. Ideally, then, the wet-bulb temperature is the lowest theoretical temperature to which the water can be cooled. Practically, the cold-water temperature approaches but does not equal the air wet-bulb temperature in a cooling tower; this is so because it is impossible to contact all the water with fresh air as the water drops through the wetted fill surface to the basin. The magnitude of approach to the wet-bulb temperature is dependent on tower design. Important factors are air-to-water contact time, amount of fill surface, and breakup of water into droplets. In actual practice, cooling towers are seldom designed for approaches closer than 2.8°C (5°F).

COOLING-TOWER THEORY

The most generally accepted theory of the cooling-tower heat-transfer process is that developed by Merkel (op. cit.). This analysis is based upon **enthalpy potential difference** as the driving force.

Each particle of water is assumed to be surrounded by a film of air, and the enthalpy difference between the film and surrounding air provides the driving force for the cooling process. In the integrated form the Merkel equation is

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{dT}{h' - h} \qquad (12\text{-}8)$$

where K = mass-transfer coefficient, lb water/(h·ft^2); a = contact area, ft^2/ft^3 tower volume; V = active cooling volume, ft^3/ft^2 of plan area; L = water rate, lb/(h·ft^2); h' = enthalpy of saturated air at water temperature, Btu/lb; h = enthalpy of air stream, Btu/lb; and T_1 and T_2 = entering and leaving water temperatures, °F. The right-hand side of Eq. (12-8) is entirely in terms of air and water properties and is independent of tower dimensions.

Figure 12-12 illustrates water and air relationships and the driving potential which exist in a counterflow tower, where air flows parallel but opposite in direction to water flow. An understanding of this diagram is important in visualizing the cooling-tower process.

The water operating line is shown by line *AB* and is fixed by the inlet and outlet tower water temperatures. The air operating line begins at *C,* vertically below *B* and at a point having an enthalpy corresponding to that of the entering wet-bulb temperature. Line *BC* represents the initial driving force ($h' - h$). In cooling water 1°F, the enthalpy per pound of air is increased 1 Btu multiplied by the ratio of pounds of water per pound of air. The liquid-gas ratio *L/G* is the slope of the operating line. The air leaving the tower is represented by point *D.* The cooling range is the projected length of line *CD* on the temperature scale. The cooling-tower approach is shown on the diagram as the difference between the cold-water temperature leaving the tower and the ambient wet-bulb temperature.

The coordinates refer directly to the temperature and enthalpy of any point on the water operating line but refer directly only to the enthalpy of a point on the air operating line. The corresponding wet-bulb temperature of any point on *CD* is found by projecting the point horizontally to the saturation curve, then vertically to the temperature coordinate. The integral [Eq. (12-8)] is represented by the area *ABCD* in the diagram. This value is known as the **tower characteristic,** varying with the *L/G* ratio.

For example, an increase in entering wet-bulb temperature moves the origin *C* upward, and the line *CD* shifts to the right to maintain a constant *KaV/L.* If the cooling range increases, line *CD* lengthens. At a constant wet-bulb temperature, equilibrium is established by moving the line to the right to maintain a constant *KaV/L.* On the other hand, a change in *L/G* ratio changes the slope of *CD,* and the tower comes to equilibrium with a new *KaV/L.*

In order to predict tower performance it is necessary to know the required tower characteristics for fixed ambient and water conditions.

The tower characteristic *KaV/L* can be determined by integration. Normally used is the Chebyshev method for numerically evaluating the integral, whereby

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{dT}{h_w - h_a} \cong \frac{T_1 - T_2}{4}\left(\frac{1}{\Delta h_1} + \frac{1}{\Delta h_2} + \frac{1}{\Delta h_3} + \frac{1}{\Delta h_4}\right)$$

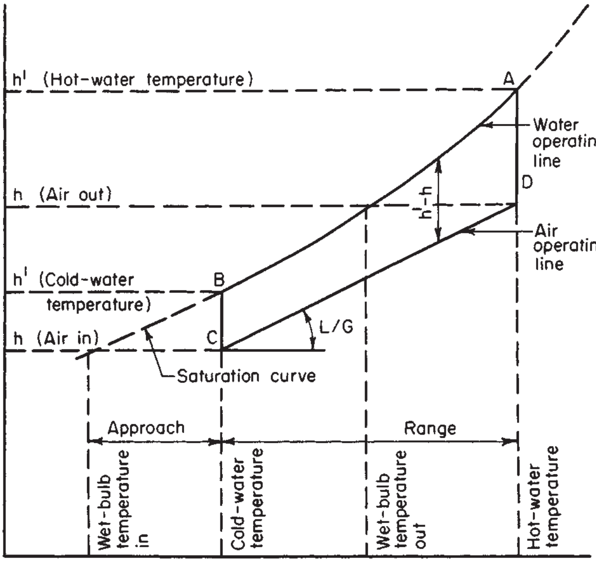

FIG. 12-12 Cooling-tower process heat balance. (*Marley Co.*)

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* The contribution of Robert W. Norris, Robert W. Norris and Associates, Inc., to material that was used from the sixth edition is acknowledged. (Evaporative Cooling)

where h_w = enthalpy of air-water vapor mixture at bulk water temperature, Btu/lb dry air
h_a = enthalpy of air-water vapor mixture at wet-bulb temperature, Btu/lb dry air
Δh_1 = value of $(h_w - h_a)$ at $T_2 + 0.1(T_1 - T_2)$
Δh_2 = value of $(h_w - h_a)$ at $T_2 + 0.4(T_1 - T_2)$
Δh_3 = value of $(h_w - h_a)$ at $T_1 - 0.4(T_1 - T_2)$
Δh_4 = value of $(h_w - h_a)$ at $T_1 - 0.1(T_1 - T_2)$

Example 9: Calculation of Mass-Transfer Coefficient Group Determine the theoretically required KaV/L value for a cooling duty from 105°F inlet water, 85°F outlet water, 78°F ambient wet-bulb temperature, and an L/G ratio of 0.97.

From air-water vapor-mixture tables, the enthalpy h_1 of the ambient air at 78°F wet-bulb temperature is 41.58 Btu/lb.

$$h_2 \text{ (leaving air)} = 41.58 + 0.97(105 - 85) = 60.98 \text{ Btu/lb}$$

T, °F.	h_{water}	h_{air}	$h_w - h_a$	$1/\Delta h$
$T_2 = 85$	49.43	$h_1 = 41.58$		
$T_2 + 0.1(20) = 87$	51.93	$h_1 + 0.1L/G(20) = 43.52$	$\Delta h_1 = 8.41$	0.119
$T_2 + 0.4(20) = 93$	60.25	$h_1 + 0.4L/G(20) = 49.34$	$\Delta h_2 = 10.91$	0.092
$T_1 - 0.4(20) = 97$	66.55	$h_2 - 0.4L/G(20) = 53.22$	$\Delta h_3 = 13.33$	0.075
$T_1 - 0.1(20) = 103$	77.34	$h_2 - 0.1L/G(20) = 59.04$	$\Delta h_4 = 18.30$	0.055
$T_1 = 105$	81.34	$h_2 = 60.98$		0.341

$$\frac{KaV}{L} = \frac{105 - 85}{4}(0.341) = 1.71$$

A quicker but less accurate method is by the use of a nomograph (Fig. 12-13) prepared by Wood and Betts (op. cit.).

Mechanical-draft cooling towers normally are designed for L/G ratios ranging from 0.75 to 1.50; accordingly, the values of KaV/L vary from 0.50 to 2.50. With these ranges in mind, an example of the use of the nomograph will readily explain the effect of changing variables.

Example 10: Application of Nomograph for Cooling-Tower Characteristics If a given tower is operating with 20°F range, a cold-water temperature of 80°F, and a wet-bulb temperature of 70°F, a straight line may be drawn on the nomograph. If the L/G ratio is calculated to be 1.0, then KaV/L may be established by a line drawn through L/G = 1.0 and parallel to the original line. The tower characteristic KaV/L is thus established at 1.42. If the wet-bulb temperature were to drop to 50°F, KaV/K and L/G ratios may be assumed to remain constant. A new line parallel to the original will then show that for the same range the cold-water temperature will be 70°F.

The nomograph provides an approximate solution; degree of accuracy will vary with changes in cooling as well as from tower to tower. Once the theoretical cooling-tower characteristic has been determined by numerical integration or from the nomograph for a given cooling duty, it is necessary to design the cooling-tower fill and air distribution to meet the theoretical tower characteristic. The Pritchard Corporation (op. cit.) has developed performance data on various tower-fill designs. These data are too extensive to include here, and those interested should consult this reference. See also Baker and Mart (Marley Co., Tech. Bull. R-52-P-10, Mission Woods, Kan.) and Zivi and Brand (loc. cit.).

MECHANICAL-DRAFT TOWERS

Two types of mechanical-draft towers are in use today: the forced-draft and the induced-draft. In the **forced-draft tower** the fan is mounted at the base, and air is forced in at the bottom and discharged at low velocity through the top. This arrangement has the advantage of locating the fan and drive outside the tower, where it is convenient for inspection, maintenance, and repairs. Since the equipment is out of the hot, humid top area of the tower, the fan is not subjected to corrosive conditions. However, because of the low exit-air velocity, the forced-draft tower is subjected to excessive recirculation of the humid

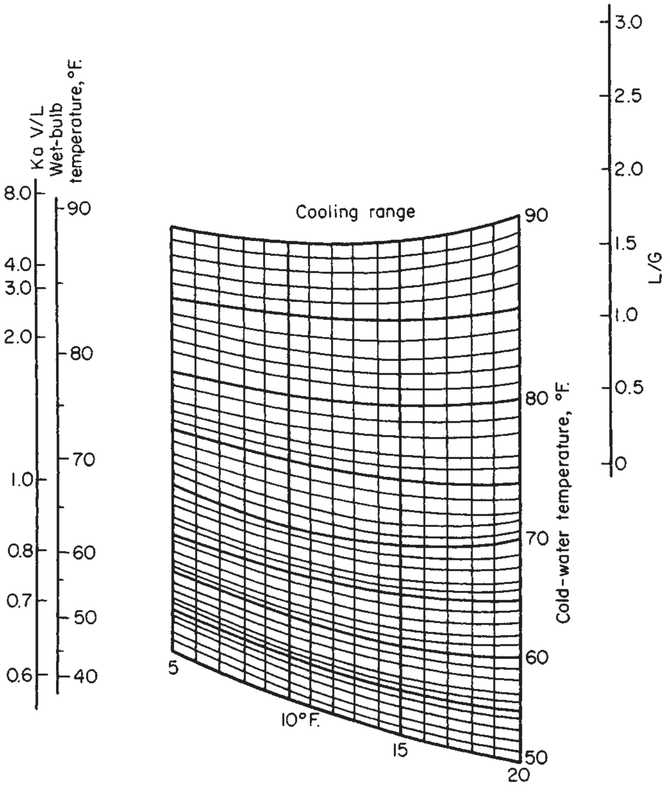

FIG. 12-13 Nomograph of cooling-tower characteristics. [*Wood and Betts,* Engineer, ***189****(4912), 337 (1950).*]

exhaust vapors back into the air intakes. Since the wet-bulb temperature of the exhaust air is considerably above the wet-bulb temperature of the ambient air, there is a decrease in performance evidenced by an increase in cold (leaving)-water temperature.

The **induced-draft tower** is the most common type used in the United States. It is further classified into counterflow and cross-flow design, depending on the relative flow directions of water and air. Thermodynamically, the **counterflow arrangement** is more efficient, since the coldest water contacts the coldest air, thus obtaining maximum enthalpy potential. The greater the cooling ranges and the more difficult the approaches, the more distinct are the advantages of the counterflow type. For example, with an L/G ratio of 1, an ambient wet-bulb temperature of 25.5°C (78°F), and an inlet water temperature of 35°C (95°F), the counterflow tower requires a KaV/L characteristic of 1.75 for a 2.8°C (5°F) approach, while a cross-flow tower requires a characteristic of 2.25 for the same approach. However, if the approach is increased to 3.9°C (7°F), both types of tower have approximately the same required KaV/L (within 1 percent).

The **cross-flow-tower** manufacturer may effectively reduce the tower characteristic at very low approaches by increasing the air quantity to give a lower L/G ratio. The increase in air flow is not necessarily achieved by increasing the air velocity but primarily by lengthening the tower to increase the air-flow cross-sectional area. It appears then that the cross-flow fill can be made progressively longer in the direction perpendicular to the air flow and shorter in the direction of the air flow until it almost loses its inherent potential-difference disadvantage. However, as this is done, fan power consumption increases.

Ultimately, the economic choice between counterflow and cross-flow is determined by the effectiveness of the fill, design conditions, and the costs of tower manufacture.

Performance of a given type of cooling tower is governed by the ratio of the weights of air to water and the time of contact between water and air. In commercial practice, the variation in the ratio of air to water is first obtained by keeping the air velocity constant at about 350 ft/(min·ft^2 of active tower area) and varying the water concentration, gal/(min·ft^2 of tower area). As a secondary operation, air velocity is varied to make the tower accommodate the cooling requirement.

Time of contact between water and air is governed largely by the time required for the water to discharge from the nozzles and fall through the tower to the basin. The time of contact is therefore obtained in a given type of unit by varying the height of the tower. Should the time of contact be insufficient, no amount of increase in the ratio of air to water will produce the desired cooling. It is therefore necessary to maintain a certain minimum height of cooling tower. When a wide approach of 8 to 11°C (15 to 20°F) to the wet-bulb temperature and a 13.9 to 19.4°C (25 to 35°F) cooling range are required, a relatively low cooling tower will suffice. A tower in which the water travels 4.6 to 6.1 m (15 to 20 ft) from the distributing system to the basin is sufficient. When a moderate approach and a cooling range of 13.9 to 19.4°C (25 to 35°F) are required, a tower in which the water travels 7.6 to 9.1 m (25 to 30 ft) is adequate. Where a close approach of 4.4°C (8°F) with a 13.9 to 19.4°C (25 to 35°F) cooling range is required, a tower in which the water travels from 10.7 to 12.2 m (35 to 40 ft) is required. It is usually not economical to design a cooling tower with an approach of less than 2.8°C (5°F), but it can be accomplished satisfactorily with a tower in which the water travels 10.7 to 12.2 m (35 to 40 ft).

Figure 12-14 shows the relationship of the hot-water, cold-water, and wet-bulb temperatures to the water concentration.* From this, the **minimum area** required for a given performance of a well-designed counterflow induced-draft cooling tower can be obtained. Figure 12-15 gives the horsepower per square foot of tower area required for a given performance. These curves do not apply to parallel or cross-flow cooling, since these processes are not so efficient as the counterflow process. Also, they do not apply when the approach to the cold-water temperature is less than 2.8°C (5°F). These charts should be considered approximate and for preliminary estimates only. Since many factors not shown in the graphs must be included in the computation, the manufacturer should be consulted for final design recommendations.

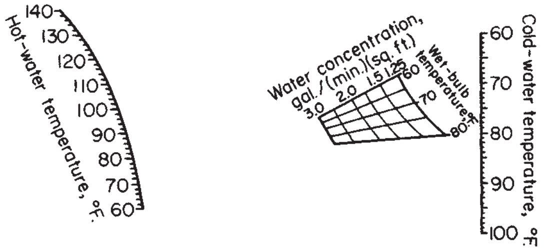

FIG. 12-14 Sizing chart for a counterflow induced-draft cooling tower, for induced-draft towers with (1) an upspray distributing system with 24 ft of fill or (2) a flume-type distributing system and 32 ft of fill. The chart will give approximations for towers of any height. *(Ecodyne Corp.)*

The cooling performance of any tower containing a given depth of filling varies with the **water concentration.** It has been found that maximum contact and performance are obtained with a tower having a water concentration of 2 to 5 gal/(min·ft^2 of ground area). Thus the problem of calculating the size of a cooling tower becomes one of determining the proper concentration of water required to obtain the desired results. Once the necessary water concentration has been established, tower area can be calculated by dividing the gallons per minute circulated by the water concentration in gallons per minute-square foot. The required tower size then is a function of the following:

1. Cooling range (hot-water temperature minus cold-water temperature)
2. Approach to wet-bulb temperature (cold-water temperature minus wet-bulb temperature)
3. Quantity of water to be cooled
4. Wet-bulb temperature
5. Air velocity through the cell
6. Tower height

Example 11: Application of Sizing and Horsepower Charts To illustrate the use of the charts, assume the following conditions:

Hot-water temperature T_1, °F = 102
Cold-water temperature T_2, °F = 78
Wet-bulb temperature t_w, °F = 70
Water rate, gal/min = 2000

A straight line on Fig. 12-14, connecting the points representing the design water and wet-bulb temperatures, shows that a water concentration of 2 gal/(min·ft^2) is required. The area of the tower is calculated as 1000 ft^2 (quantity of water circulated divided by water concentration).

Fan horsepower is obtained from Fig. 12-15. Connecting the point representing 100 percent of standard tower performance with the turning point and extending this straight line to the horsepower scale show that it will require 0.041 hp/ft^2 of actual effective tower area. For a tower area of 1000 ft^2 41.0 fan hp is required to perform the necessary cooling.

Suppose that the actual commercial tower size has an area of only 910 ft^2. Within reasonable limits, the shortage of actual area can be compensated for by an increase in air velocity through the tower. However, this requires boosting fan horsepower to achieve 110 percent of standard tower performance. From Fig. 12-15, the fan horsepower is found to be 0.057 hp/ft^2 of actual tower area, or $0.057 \times 910 = 51.9$ hp.

On the other hand, if the actual commercial tower area is 1110 ft^2, the cooling equivalent to 1000 ft^2 of standard tower area can be accomplished with less air and less fan horsepower. From Fig. 12-15, the fan horsepower for a tower operating at 90 percent of standard performance is 0.031 hp/ft^2 of actual tower area, or 34.5 hp.

This example illustrates the sensitivity of fan horsepower to small changes in tower area. The importance of designing a tower that is slightly oversize in ground area and of providing plenty of fan capacity becomes immediately apparent.

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[*] See also London, Mason, and Boelter, loc. cit.; Lichtenstein, loc. cit.; Simpson and Sherwood, *J. Am. Soc. Refrig. Eng.*, **52,** 535, 574 (1946); Simons, *Chem. Metall. Eng.*, **49**(5), 138; (6), 83 (1942); **46,** 208 (1939); and Hutchinson and Spivey, *Trans. Inst. Chem. Eng.*, **20,** 14 (1942).

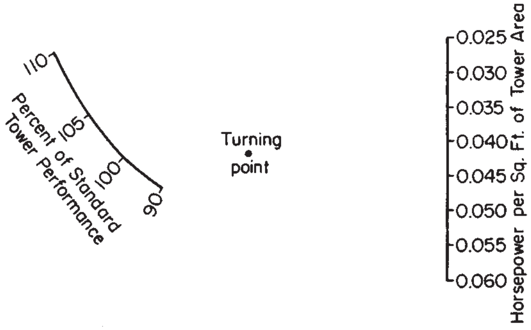

FIG. 12-15 Horsepower chart for a counterflow induced-draft cooling tower. [*Fluor Corp. (now Ecodyne Corp.)*]

Example 12: Application of Sizing Chart Assume the same cooling range and approach as used in Example 11 except that the wet-bulb temperature is lower. Design conditions would then be

$$\text{Water rate, gal/min} = 2000$$
$$\text{Temperature range } (T_1 - T_2), °\text{F} = 24$$
$$\text{Temperature approach } (T_2 - t_w), °\text{F} = 8$$
$$\text{Hot-water temperature } T_1, °\text{F} = 92$$
$$\text{Cold-water temperature } T_2, °\text{F} = 68$$
$$\text{Wet-bulb temperature } t_w, °\text{F} = 60$$

From Fig. 12-14, the water concentration required to perform the cooling is 1.75 gal/(min·ft^2), giving a tower area of 1145 ft^2 versus 1000 ft^2 for a 70°F wet-bulb temperature. This shows that the lower the wet-bulb temperature for the same cooling range and approach, the larger is the area of the tower required and therefore the more difficult is the cooling job.

Figure 12-16 illustrates the type of performance curve furnished by the cooling-tower manufacturer. This shows the variation in performance with changes in wet-bulb and hot-water temperatures while the water quantity is maintained constant.

COOLING-TOWER OPERATION

Water Makeup Makeup requirements for a cooling tower consist of the summation of evaporation loss, drift loss, and blowdown. Therefore,

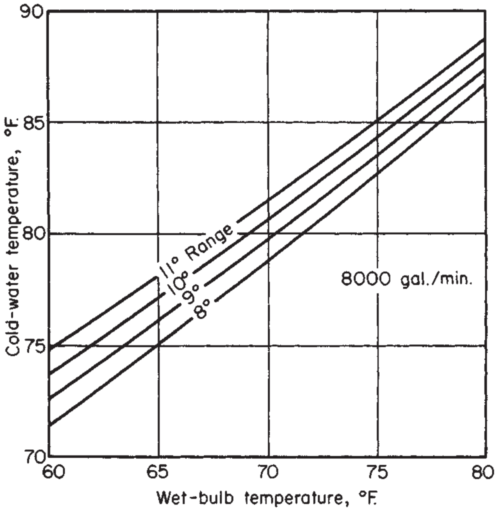

FIG. 12-16 Typical cooling-tower performance curve.

$$W_m = W_e + W_d + W_b \qquad (12\text{-}9)$$

where W_m = makeup water, W_d = drift loss, and W_b = blowdown [consistent units, m^3/(h·gal·min)].

Evaporation loss can be estimated by the following equation:

$$W_e = 0.00085\ W_c(T_1 - T_2) \qquad (12\text{-}10)$$

where W_c = circulating-water flow, gal/min at tower inlet
$T_1 - T_2$ = inlet-water temperature minus outlet-water temperature, °F

Drift is entrained water in the tower discharge vapors. Drift loss is a function of the drift-eliminator design, which typically varies between 0.1 and 0.2 percent of the water supplied to the tower. New developments in eliminator design make it possible to reduce drift loss well below 0.1 percent.

Blowdown discards a portion of the concentrated circulating water due to the evaporation process in order to lower the system solids concentration. The amount of blowdown can be calculated according to the number of cycles of concentration required to limit scale formation. Cycles of concentration are the ratio of dissolved solids in the recirculating water to dissolved solids in the makeup water. Since chlorides remain soluble on concentration, cycles of concentration are best expressed as the ratio of the chloride content of the circulating and makeup waters. Thus, the blowdown quantities required are determined from

$$\text{Cycles of concentration} = (W_e + W_b)/W_b \qquad (12\text{-}11)$$

or

$$W_b = W_e/(\text{cycles} - 1) \qquad (12\text{-}12)$$

Cycles of concentration involved with cooling-tower operation normally range from three to five cycles. Below three cycles of concentration, excessive blowdown quantities are required and the addition of acid to limit scale formation should be considered.

Example 13: Calculation of Makeup Water Determine the amount of makeup required for a cooling tower with the following conditions:

Inlet water flow, m^3/h (gal/min)	2270	(10,000)
Inlet water temperature, °C (°F)	37.77	(100)
Outlet water temperature, °C (°F)	29.44	(85)
Drift loss, percent	0.2	
Concentration, cycles	5	

Evaporation loss

$$W_e,\ \text{m}^3/\text{h} = 0.00085 \times 2270 \times (37.77 - 29.44) \times 1.8$$
$$= 28.9$$
$$W_e,\ \text{gal/min} = 127.5$$

Drift loss

$$W_d,\ \text{m}^3/\text{h} = 2270 \times 0.002 = 4.54$$
$$W_d,\ \text{gal/min} = 20$$

Blowdown

$$W_b,\ \text{m}^3/\text{h} = \frac{W_e}{(S-1)} = \frac{28.9}{4} = 7.24$$
$$W_b,\ \text{gal/min} = 31.9$$

Makeup

$$W_m,\ \text{m}^3/\text{h} = 28.9 + 4.54 + 7.24 = 40.7$$
$$W_m,\ \text{gal/min} = 179.4$$

Fan Horsepower In evaluating cooling-tower owning and operating costs, fan-horsepower requirements can be a significant factor. Large air quantities are circulated through cooling towers at exit velocities of about 10.2 m/s (2000 ft/min) maximum for induced-draft towers. Fan air-flow quantities depend upon tower-design factors, including such items as type of fill, tower configuration, and thermal-performance conditions.

The effective output of the fan is static air horsepower (SAHP), which is obtained by the following equation:

$$\text{SAHP} = \frac{Q(h_s)(d)}{33{,}000(12)} \tag{12-13}$$

where Q = air volume, ft^3/min; h_s = static head, in of water; and d = density of water at ambient temperature, lb/ft^3.

Cooling-tower fan horsepower can be reduced substantially as the ambient wet-bulb temperature decreases if two-speed fan motors are used. Theoretically, operating at half speed will reduce air flow by 50 percent while decreasing horsepower to one-eighth of full-speed operation. However, actual half-speed operation will require about 17 percent of the horsepower at full speed as a result of the inherent motor losses at lighter loads.

Figure 12-17 shows a typical plot of outlet-water temperatures when a cooling tower is operated (1) in the fan-off position, (2) with the fan at half speed, and (3) with the fan at full speed. Note that at decreasing wet-bulb temperatures the water leaving the tower during half-speed operation could meet design water-temperature requirements of, say, 85°F. For example, for a 60°F wet-bulb, 20°F range, a leaving-water temperature slightly below 85°F is obtained with design water flow over the tower. If the fan had a 100-hp motor, 83 hp would be saved when operating it at half speed. In calculating savings, one should not overlook the advantage of having colder tower water available for the overall water-circulating system.

Recent developments in cooling-tower fan energy management also include automatic variable-pitch propeller-type fans and inverter-type devices to permit variable fan speeds. These schemes involve tracking the load at a *constant* leaving-water temperature.

The variable-pitch arrangement at constant motor speed changes the pitch of the blades through a pneumatic signal from the leaving-water temperature. As the thermal load and/or the ambient wet-bulb temperature decreases, the blade pitch reduces air flow and less fan energy is required.

Inverters make it possible to control a variable-speed fan by changing the frequency modulation. Standard alternating-current fan motors may be speed-regulated between 0 and 60 Hz. In using inverters for this application, it is important to avoid frequencies that would result in fan critical speeds.

Even though tower-fan energy savings can result from these arrangements, they may not constitute the best system approach. Power-plant steam condensers and refrigeration units, for example, can take advantage of colder tower water to reduce power consumption. Invariably, these system savings are much larger than cooling-tower fan savings with constant leaving-water temperatures. A refrigeration-unit condenser can utilize inlet-water temperatures down to 12.8°C (55°F) to reduce compressor energy consumption by 25 to 30 percent.

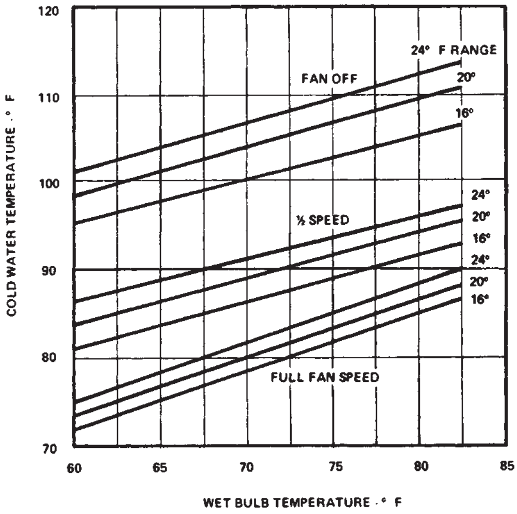

FIG. 12-17 Typical plot of cooling-tower performance at varying fan speeds.

Pumping Horsepower Another important factor in analyzing cooling-tower selections, especially in medium to large sizes, is the portion of pump horsepower directly attributed to the cooling tower. A counterflow type of tower with spray nozzles will have a pumping head equal to static lift plus nozzle pressure loss. A cross-flow type of tower with gravity flow enables a pumping head to equal static lift. A reduction in tower height therefore reduces static lift, thus reducing pump horsepower:

$$\text{Pump bhp} = \frac{\text{gal/min}(h_t)}{3960\ (\text{pump efficiency})} \tag{12-14}$$

where h_t = total head, ft.

Fogging and Plume Abatement A phenomenon that occurs in cooling-tower operation is fogging, which produces a highly visible plume and possible icing hazards. Fogging results from mixing warm, highly saturated tower discharge air with cooler ambient air that lacks the capacity to absorb all the moisture as vapor. While in the past visible plumes have not been considered undesirable, properly locating towers to minimize possible sources of complaints has now received the necessary attention. In some instances, guyed high fan stacks have been used to reduce ground fog. Although tall stacks minimize the ground effects of plumes, they can do nothing about water-vapor saturation or visibility. The persistence of plumes is much greater in periods of low ambient temperatures.

More recently, environmental aspects have caused public awareness and concern over any visible plume, although many lay persons misconstrue cooling-tower discharge as harmful. This has resulted in a new development for plume abatement known as a wet-dry cooling-tower configuration. Reducing the relative humidity or moisture content of the tower discharge stream will reduce the frequency of plume formation. Figure 12-18 shows a "parallel path" arrangement that has been demonstrated to be technically sound but at substantially increased tower investment. Ambient air travels in parallel streams through the top dry-surface section and the evaporative section. Both sections benefit thermally by receiving cooler ambient air with the wet and dry air streams mixing after leaving their respective sections. Water flow is arranged in series, first flowing to the dry-coil section and then to the evaporation-fill section. A "series path" air-flow arrangement, in which dry coil sections can be located before or after the air traverses the evaporative section, also can be used. However, series-path air flow has the disadvantage of water impingement, which could result in coil scaling and restricted air flow.

Wet-dry cooling towers incorporating these designs are being used for large-tower industrial applications. At present they are not available for commercial applications.

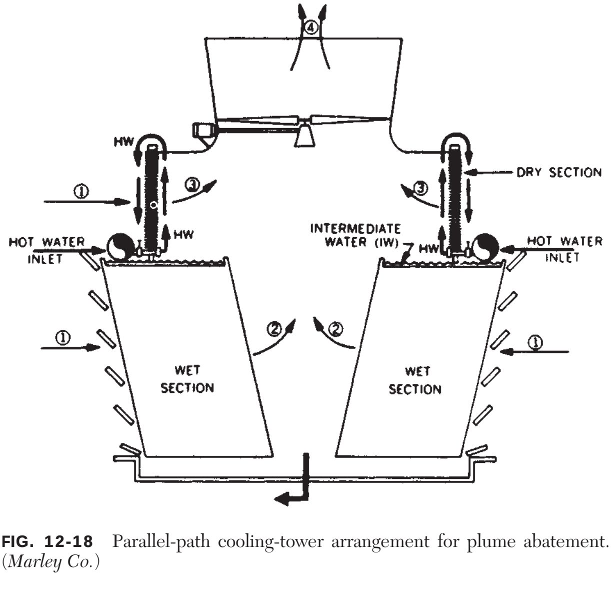

FIG. 12-18 Parallel-path cooling-tower arrangement for plume abatement. (*Marley Co.*)

Energy Management With today's emphasis on energy management, cooling towers have not been overlooked. During periods below 50°F ambient wet-bulb temperatures, cooling towers have the temperature capability to furnish chilled water directly to air-conditioning systems. For existing refrigeration–cooling-tower systems, piping can be installed to bypass the chiller to allow tower effluent to flow directly to cooling coils. After heat has been removed from the air stream, water returns directly to the cooling tower. Water temperature leaving the cooling tower is controlled between 8.9 and 12.2°C (48 and 54°F), usually by cycling cooling-tower fans. Depending upon the cleanliness of the cooling-tower water, it may be necessary to install a side-stream or full-flow filter to minimize contamination of the normally closed chilled-water circuit. Figure 12-19 shows the general arrangement of this system. Substantial savings can be realized during colder months by eliminating refrigeration-compressor energy.

Several other methods involving cooling towers have been used to reduce refrigeration energy consumption. These systems, as applied to centrifugal and absorption refrigeration machines, are known as thermocycle or free cooling systems. When water leaving the cooling tower is available below 10°C (50°F), the thermocycle system permits shutting down the compressor prime mover or reducing steam flow to an absorption unit. Figure 12-20 shows the arrangement for a centrifugal refrigeration unit.

The thermocycle system can be operated only when condensing water is available at a temperature lower than the required chilled-water-supply temperature. Modifications for a centrifugal refrigeration unit include the installation of a small liquid-refrigerant pump, cooler spray header nozzles, and a vapor bypass line between the cooler and the condenser. Without the compressor operating, a thermocycle capacity up to 35 percent of the refrigeration-unit rating can be produced.

The cooling-tower fan is operated at full speed to produce the coldest water temperature possible for a given ambient wet-bulb temperature. The large vapor bypass between the cooler and the condenser is opened along with the compressor suction damper or prerotational vanes. The heat removed from the chilled-water stream boils off refrigerant vapor from the cooler. This vapor flows mainly through the bypass line to the condenser, where it is condensed to a liquid. (Units having hot-gas bypass lines cannot be used for this purpose, as the pipe size is too small.) The liquid then returns to the cooler as in the normal refrigeration cycle. If the refrigeration unit contains internal float valves, they are bypassed manually or held open by an adjusting stem.

Thermocycle capacity is a function of the temperature difference between the chilled-water outlet temperature leaving the cooler and the inlet condenser water. The cycle finally stops when these two temperatures approach each other and there is not sufficient vapor pressure difference to permit flow between the heat exchangers.

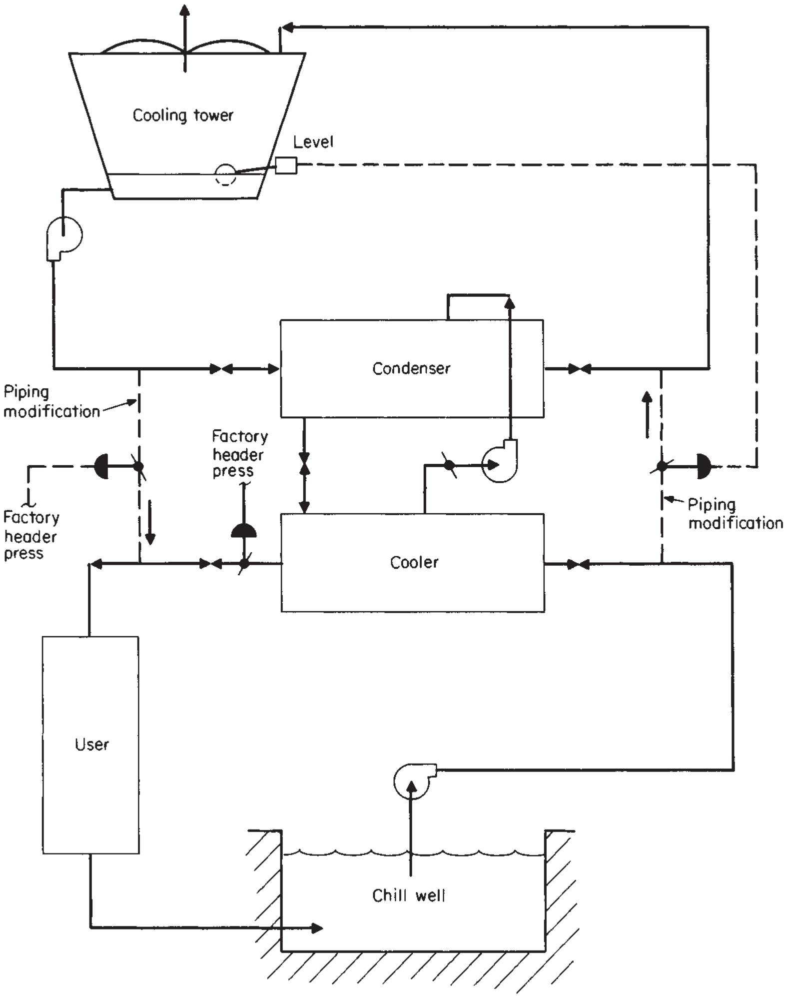

FIG. 12-19 Cooling-tower water for direct cooling during winter months.

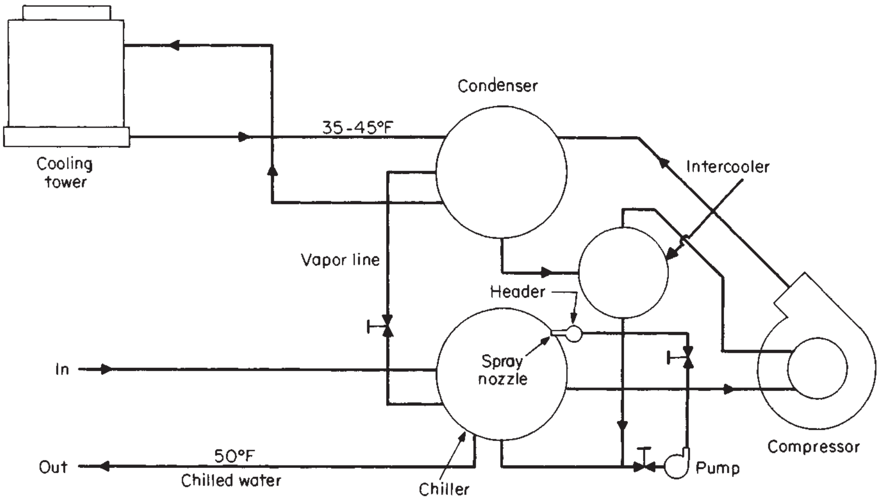

FIG. 12-20 Cooling-tower use on a thermocycle system during winter months.

Precise control of the outlet chilled-water temperature does not occur with thermocycle operation. This temperature is dependent on ambient wet-bulb-temperature conditions. Normally, during cold winter days little change occurs in wet-bulb temperatures, so that only slight water-temperature variations may occur. This would not be true of many spring and fall days, when relatively large climatic temperature swings can and do occur.

Refrigeration units modified for free cooling do not include the liquid-refrigerant pump and cooler spray header nozzles. Without the cooler refrigerant agitation for improved heat transfer, this arrangement allows up to about 20 percent of rated capacity. Expected capacities for both thermocycle and free cooling are indicated in Fig. 12-21.

In operating a cooling tower in the thermocycle or free-cooling mode, some precautions are necessary to minimize icing problems. These include fan reversals to circulate air down through the tower inlet louvers, proper water distribution, constant water flow over the tower, heat tracing of lines such as makeup lines as required, and maximum loading per tower cell.

NATURAL-DRAFT TOWERS

Natural-draft, or hyperbolic-type, towers have been in use since about 1916 in Europe and have become standard equipment for the water-cooling requirements of British power stations. They are primarily

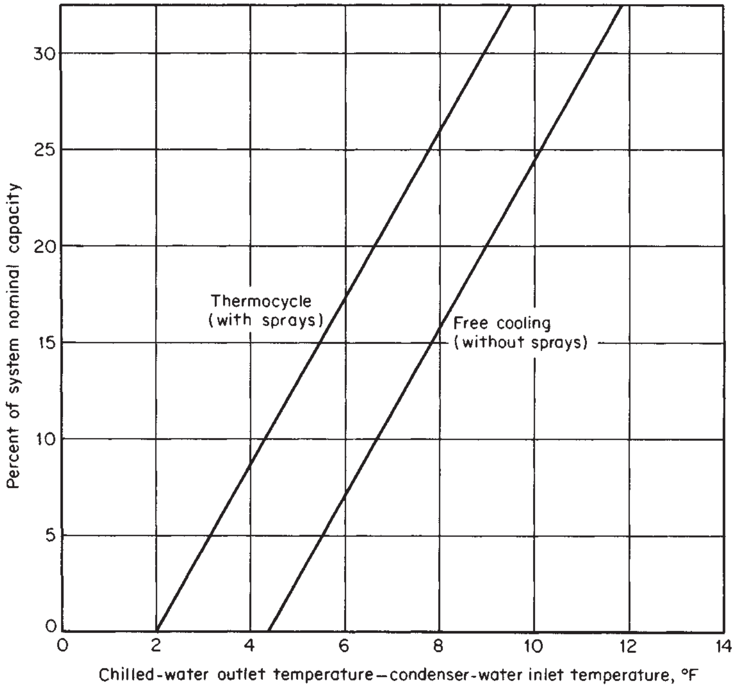

FIG. 12-21 Thermocycle and free-cooling-system capacities.

suited to very large cooling-water quantities, and the reinforced-concrete structures used are as large as diameters of 80.7 m (265 ft) and heights of 103.6 m (340 ft).

The design convenience obtained from the steady air flow of mechanical-draft towers is not realized in natural-draft-tower design. Air flow through a natural-draft tower is due largely to the difference in density between the cool inlet air and the warm exit air. The air leaving the stack is lighter than the ambient air, and a draft is created by chimney effect, thus eliminating the need for mechanical fans. McKelvey and Brooke (*The Industrial Cooling Tower,* Elsevier, New York, 1959, p. 108) note that natural-draft towers commonly operate at air-pressure differences in the region of 0.2-in water gauge when under full load. The mean velocity of the air above the tower packing is generally about 1.2 to 1.8 m/s (4 to 6 ft/s).

The performance of the natural-draft tower differs from that of the mechanical-draft tower in that the cooling is dependent upon the relative humidity as well as on the wet-bulb temperature. The draft will increase through the tower at high-humidity conditions because of the increase in available static pressure difference to promote air flow against internal resistances. Thus the higher the humidity at a given wet bulb, the colder the outlet water will be for a given set of conditions. This fundamental relationship has been used to advantage in Great Britain, where relative humidities are commonly 75 to 80 percent. Therefore, it is important in the design stages to determine correctly and specify the density of the entering and effluent air in addition to the usual tower-design conditions of range, approach, and water quantity. The performance relationship to humidity conditions makes exact control of outlet-water temperature difficult to achieve with the natural-draft tower.

Data for determining the size of natural-draft towers have been presented by Chilton [*Proc. Inst. Elec. Eng.*, **99,** 440 (1952)] and Rish and Steel (ASCE Symposium on Thermal Power Plants, October 1958). Chilton showed that the duty coefficient D_t of a tower is approximately constant over its normal range of operation and is related to tower size by an efficiency factor or performance coefficient C_t as follows:

$$D_t = (A\sqrt{Z_t})/(C_t\sqrt{C_t}) \qquad (12\text{-}15)$$

where A = base area of tower, ft², measured at pond sill level; and Z_t = height of tower, ft, measured above sill level. The duty coefficient may be determined from the formula

$$(W_L/D_t) = 90.59(\Delta h/\Delta T)\sqrt{\Delta t + 0.3124\Delta h} \qquad (12\text{-}16)$$

where Δh = change in total heat of the air passing through the tower, Btu/lb; ΔT = change of water temperature passing through tower, °F; Δt = difference between air temperature leaving the packing and inlet dry-bulb temperature, °F; and W_L = water load in the tower, lb/h. The air leaving the packing inside the tower is assumed to be saturated at a temperature halfway between the inlet- and outlet-water temperatures. A divergence between theory and practice of a few degrees in this latter assumption does not significantly affect the results, as the draft component depends on the ratio of the change of density to change of total heat and not on change of temperature alone.

Example 14: Duty Coefficient for a Hyperbolic Tower Determine the duty coefficient for a hyperbolic tower operating with

Temperature of water to tower, °F = 82
Leaving (recooled) water temperature, °F = 70
Temperature range ΔT, °F = 12
Dry-bulb air temperature t_2, °F = 57
Aspirated (ambient) wet-bulb air temperature t_{w2}, °F = 51.7
Water loading to tower W_L, lb/h = 38,200,000

$$t_1 = (82° + 70°)/2 = 76° \qquad h_1 = 39.8 \text{ (from Fig. 12-2)}$$

$$t_2 = \underline{57°} \qquad h_2 = \underline{21.3}$$

$$\Delta t = 19° \qquad \Delta h = 18.5$$

$$W_L/D_t = 90.59(18.5/12)\sqrt{19 + 0.3124(18.5)} = 696$$

$$D_t = 38{,}200{,}000/696 = 55{,}000$$

The performance coefficients usually attained have been about 5.2 for water loadings in excess of 750 lb/(h·ft²), though new types of packing are improving (lowering) it. By taking a C_t value of 5.0 and a tower height of 320 ft, the base area of the tower will be $(55{,}000)(5\sqrt{5})/\sqrt{320} = 34{,}600$ ft², or the internal base diameter at sill level will be 210 ft. A ratio of height to base diameter of 3:2 is normally employed.

To determine how a natural-draft tower of any given duty coefficient will perform under varying conditions, Rish and Steel plotted the nomograph in Fig. 12-22. The straight line shown on the nomograph illustrates the conditions of Example 14.

SPRAY PONDS

Spray ponds provide an arrangement for lowering the temperature of water by evaporative cooling and, in so doing, greatly reduce the cooling area required in comparison with a cooling pond. A spray pond uses a number of nozzles which spray water into contact with the surrounding air. A well-designed spray nozzle should provide fine water drops but should not produce a mist which would be carried off as excessive drift loss.

Table 12-3 provides design data which will assist in the layout of a spray pond. The pond should be placed with its long axis at right angles to the prevailing summer wind. A long, narrow pond is more effective than a square one, so that decreasing pond width and increasing pond length will improve performance. Performance can also be increased by decreasing the amount of water sprayed per unit of pond area, increasing the height and fineness of spray drops, and increasing nozzle height above the basin sides.

Sufficient distance should be provided from the outer nozzles to keep spray from being carried over the sides of the basin. If it is not possible to provide 7.6 to 10.7 m (25 to 35 ft) of space, the pond should be enclosed with a louver fence, equal in height to the maximum height of the spray, to minimize drift loss. Also, during cold-weather periods, fogging can occur from the spray pond, so that consideration should be given to possible hazards to roadways or buildings in the immediate vicinity.

The physical designs and operating conditions of spray-pond installations vary greatly, and it is difficult to develop exact rating data that can be used for determining cooling performance in all cases. However, Fig. 12-23 shows the performance that can be obtained with a well-designed spray pond, based on a 21.1°C (70°F) wet-bulb temperature and a 2.2-m/s (5-mi/h) wind. This curve shows that a 3.3°C (6°F) approach to the wet bulb is possible at a 2.2°C (4°F) range, but at higher ranges the obtainable approach increases. If it is necessary to cool water through a large temperature range to a reasonably close approach, the spray pond could be staged. With this method, the water is initially sprayed, collected, and then resprayed in another part of a sectionalized pond basin.

Figure 12-24 shows performance curves for a spray pond used in steam-condensing service at varying wet-bulb and range conditions. Spray-pond performance can be calculated within reasonable accuracy on the basis of the leaving wet-bulb temperature of the air passing through the spray-filled volume. The air temperature leaving cannot exceed the warm water to the pond, and the closeness of approach will depend on the pond layout. In calculating the cooling obtained, the spray-filled volume is figured from a height equal to the elevation of the nozzles above the pond surface plus 0.3 m (1 ft) for each 7-kPa (1bf/in²) nozzle pressure and a plan area extending 3 m (10 ft) beyond the outer nozzles. The air area involved is the projected area of a vertical plane through the filled volume and broadside to the direction of air movement. The horizontal distance that the air moves through the filled volume is considered the length of air travel.

Example 15: Cooling Capacity of a Spray Pond Determine the cooling capacity of a spray pond operating at the following conditions:

Water flow, gal/min	46,000
Spray-nozzle pressure, lb/in²	7
Water flow per nozzle, gal/min	42.5
Effective area, length × width, ft²	434 × 100
Effective height, ft	7 + 7 spray height
Wind velocity, ft/min	440

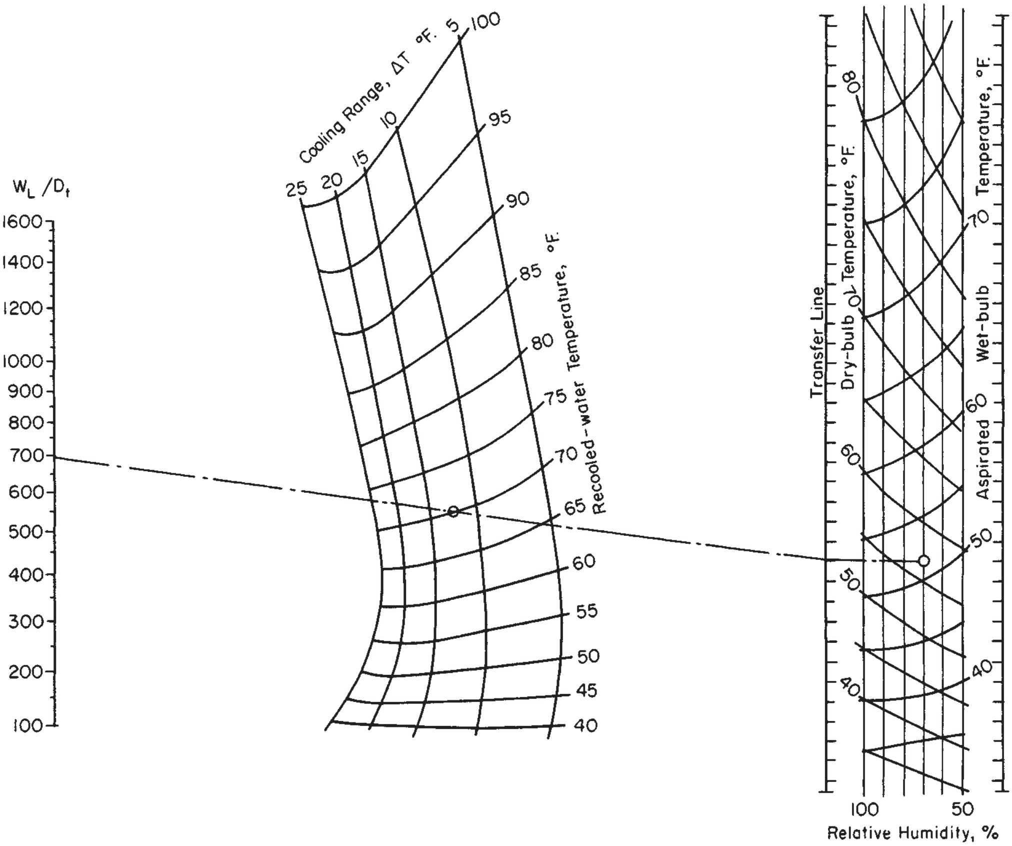

FIG. 12-22 Universal performance chart for natural-draft cooling towers. (*Rish and Steel,* ASCE Symposium on Thermal Power Plants, *October 1958.*)

Prevailing wind	Broadside to pond
Ambient wet-bulb temperature, °F	78
Water temperature in, °F	102

$$\text{Effective air area} = 434 \times 14 = 6080 \text{ ft}^2$$

$$\text{Air flow} = 440 \times 6080 = 2{,}680{,}000 \text{ ft}^3/\text{min}$$

$$L = 46{,}000 \times 8.33 = 384{,}000 \text{ lb water/min}$$

$$G = 2{,}680{,}000/14.3 = 187{,}500 \text{ lb air/min}$$

$$L/G = 384{,}000/187{,}500 = 2.05$$

h' at 78°F wet-bulb temperature = 41.58 Btu/lb (from Table 12-1). Assume water temperature out = 92°F.

TABLE 12-3 Spray-Pond Engineering Data and Design*

Recommendations	Usual	Minimum	Maximum
Nozzle capacity, gal./min. each	35–50	10	60
Nozzles per 12-ft. length of pipe	5–6	4	8
Height of nozzles above sides of basin, ft.	7–8	2	10
Nozzle pressure, lb./sq. in.	5–7	4	10
Size of nozzles and nozzle arms, in.	2	1¼	2½
Distance between spray lateral piping, ft.	25	13	38
Distance of nozzles from side of pond, unfenced, ft.	25–35	20	50
Distance of nozzles from side of pond, fenced, ft.	12–18	10	25
Height of louver fence, ft.	12	6	18
Depth of pond basin, ft.	4–5	2	7
Friction loss per 100 ft. pipe, in. of water	1–3	—	6
Design wind velocity, m.p.h.	5	3	10

*From Spray Pond Bull. SP-51, Marley Co., Mission Woods, Kan., p. 3.

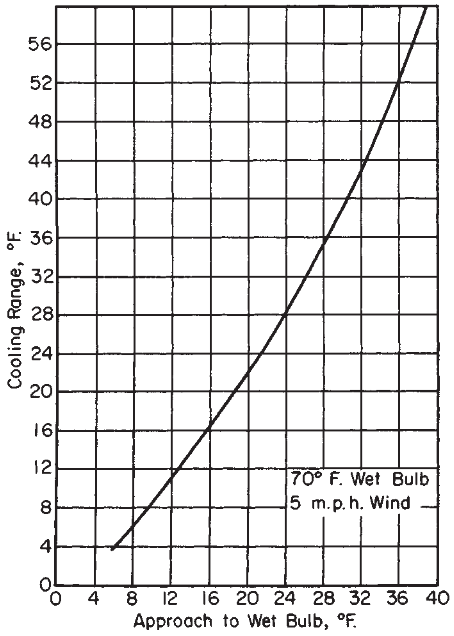

FIG. 12-23 Spray-pond performance curve.

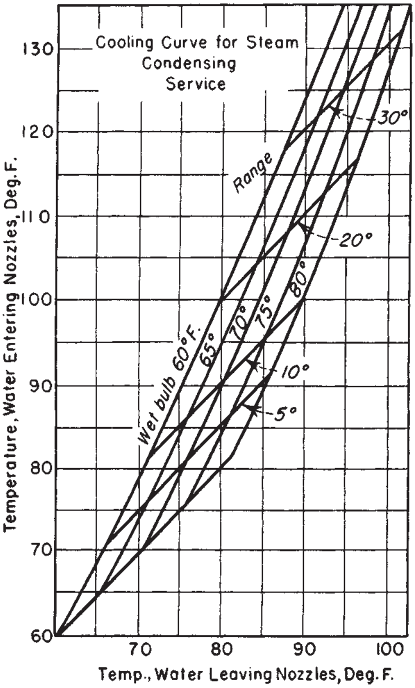

FIG. 12-24 Spray ponds: cooling curves for steam-condensing service.

$$\frac{L}{G} = \frac{(h_2') \text{ air out} - (h_1') \text{ air in}}{\text{water temperature in} - \text{water temperature out}} = 2.05 = \frac{h_2' - 41.58}{10}$$

$$h_2' = 61.63 \text{ Btu/lb}$$

Corresponding wet-bulb temperature = 94°F air leaving pond.
Approach possible to air leaving (from Table 12-4) = −2°F.
Water temperature leaving spray pond = 94°F − 2°F = 92°F.

Since leaving-water temperature checks assumption, spray pond is capable of cooling 46,000 gal/min from 102 to 92°F with 78°F wet-bulb temperature and 5-mi/h wind. Total of 1080 spray nozzles required at 42.5 gal/min each, nozzles at 7-lbf/in² pressure.

COOLING PONDS

When large ground areas are available, cooling ponds offer a satisfactory method of removing heat from water. A pond may be constructed at a relatively small investment by pushing up an earth dike 1.8 to 3.1 m (6 to 10 ft) high. For a successful pond installation, the soil must be reasonably impervious, and location in a flat area is desirable. Four principal heat-transfer processes are involved in obtaining cooling from an open pond. Heat is lost through evaporation, convection, and radiation and is gained through solar radiation. The required pond area depends on the number of degrees of cooling required and the net heat loss from each square foot of pond surface.

TABLE 12-4 Degree Adjustment to Be Applied to Leaving-Air Wet-Bulb Temperature to Find Cooled-Water Temperatures of Spray Ponds*

Cooling range, °F.	Entering wet-bulb temp., † °F.	Adjustment, °F. Length of air travel, ft.‡ 100	50	25
10	80	−3	+2	+4
	70	−2	+3	+5
	60	−1.5	+3.5	+5.5
15	80	−5.0	+1	+5
	70	−4.0	+2	+5.5
	60	−3.5	+2.5	+6
20	80	−7	0	+6
	70	−6	+1	+7
	60	−5.5	+1.5	+7.5

Cooled-water temperature = wet-bulb temperature of leaving air plus values shown.

*From "Heating, Ventilating, Air Conditioning Guide," 38th ed., p. 598 American Society of Heating, Refrigerating and Air Conditioning Engineers 1960.

†Wet-bulb temperature of air entering spray-filled volume.

‡Length of air travel through spray-filled volume.

Langhaar [*Chem. Eng.*, **60**(8), 194 (1953)] states that under given atmospheric conditions a body of water would eventually come to a temperature at which heat loss would equal heat gain. This temperature is referred to as the equilibrium temperature and is designated as *E* in Fig. 12-25, a nomograph of cooling-pond performance. The equilibrium temperature is greatly affected by the amount of solar radiation, which is usually not known very accurately and which varies throughout the day. If a pond has at least a 24-h holdup, then daily average weather conditions may be used. For practical purposes, it is recommended that the equilibrium temperature be taken as equal to normal river-water or lake temperature for the specified weather conditions.

In order to cool to the equilibrium temperature, a pond of infinite size would be required for warm water. An approach of 1.7 to 2.2°C (3 to 4°F) is the lowest practicable in a pond of reasonable size. For a pond having more than a 24-h holdup, the leaving-water temperature will vary from the average by plus or minus 1.1°C (2°F) for a 0.9-m (5-ft) depth and 1.7°C (3°F) variation for a 0.9-m (3-ft) depth.

The area of pond required for a given cooling load is almost independent of pond depth. A depth of at least 0.9 m (3 ft) appears advisable to prevent excessive channeling of flow with ponds having irregular bottoms and to avoid large day-to-night changes in outlet temperature.

Factors considered to affect pond performance are air temperature, relative humidity, wind speed, and solar radiation. Items appearing to have only a minor effect include heat transfer between the earth and the pond, changing temperature and humidity of the air as it traverses the water, and rain.

Figure 12-25 provides a rapid method of determining the pond-area requirements for a given cooling duty. D_1 and D_2 are the approaches to equilibrium for the entering and leaving water, °F; V_w is the wind velocity, mi/h; product *PQ* represents the area of the pond surface, ft²/(gal·min) of flow to the pond. The *P* factor assumes a pond with uniform flow, without turbulence, and with the water warmer than the air.

Example 16: Calculation of Cooling-Pond Size Determine the required size of a cooling pond operating at the following conditions:

Relative humidity, percent = 50
Wind velocity, mi/h = 5
Dry-bulb air temperature, °F = 68
Solar heat gain, Btu/(h·ft²) = 100
Water quantity, gal/min = 10,000

TABLE 12-5 Maximum Expected Solar Radiation at Various North Latitudes*

B.t.u./(hr.)(sq. ft.)

	24-hr. avg. at north latitude 30°	35°	40°	45°	Noon value at north latitude 30°	35°	40°	45°
Jan. 1	65	50	40	30	240	205	170	135
Feb. 1	75	65	55	45	270	240	210	175
Mar. 1	90	80	75	65	305	285	255	230
Apr. 1	110	105	95	90	340	320	300	280
May 1	120	120	120	115	360	350	335	320
June 1	130	130	130	130	365	360	345	335
July 1	130	130	130	130	365	360	350	340
Aug. 1	125	125	125	120	360	350	340	325
Sept. 1	115	110	105	100	350	335	315	300
Oct. 1	100	90	80	75	315	295	270	245
Nov. 1	80	70	60	50	270	245	215	185
Dec. 1	65	55	45	35	240	210	175	140

*Langhaar, *Chem. Eng.*, **60**(8), 194 (1953).

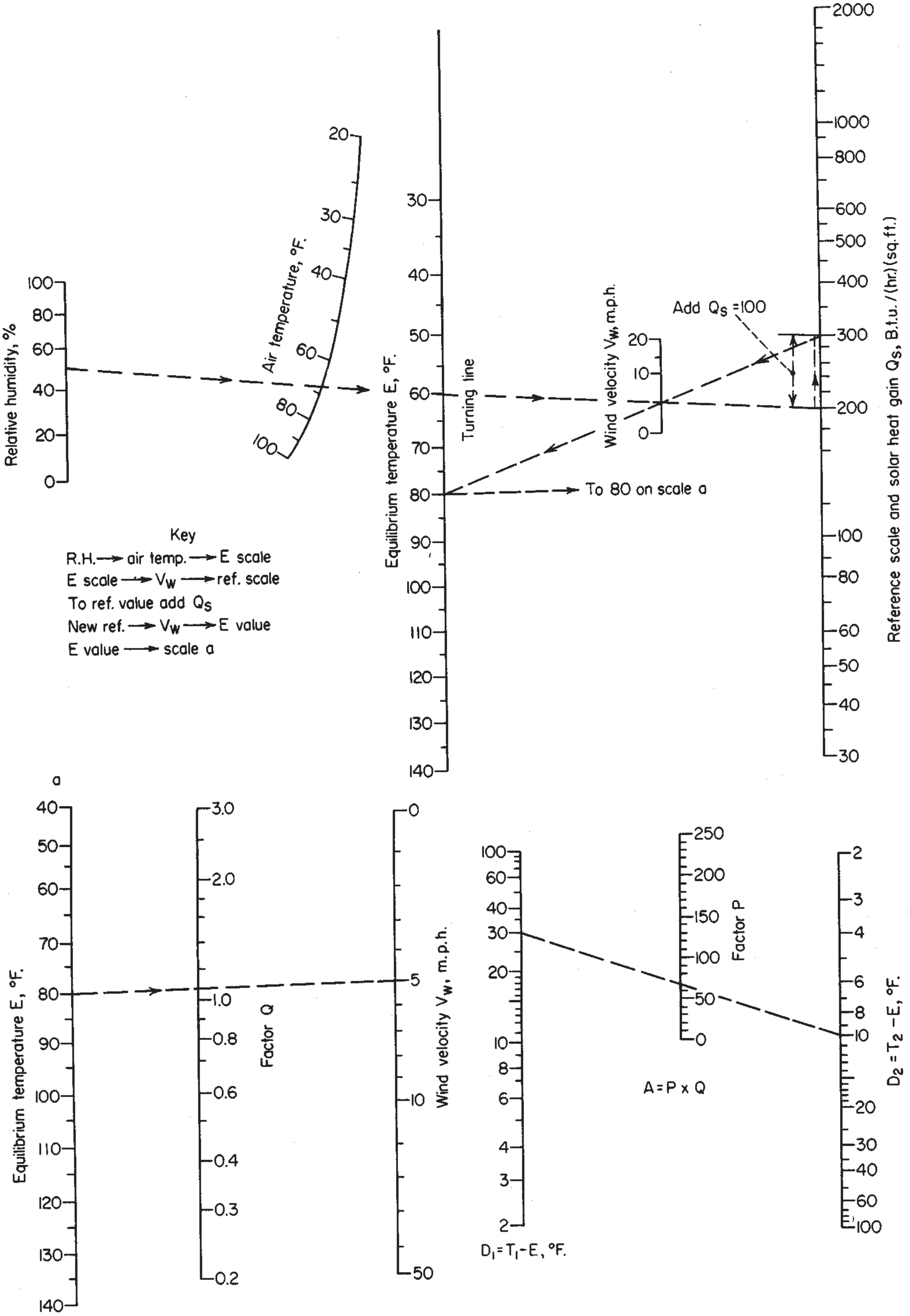

FIG. 12-25 Nomograph for determining cooling-pond performance and size. [*Langhar,* Chem. Eng., ***60***(8), *194 (1953).*]

Water inlet, °F = 110

Water outlet, °F = 90

From the nomograph, $P = 68$ and $Q = 1.07$, giving an area required of 73 ft^2/(gal·min). Area for 10,000 gal/min is thus 730,000 ft^2, or 17 acres.

With a depth of 5 ft, total volume of the pond would amount to a 45.5-h holdup, which is more than the 24-h holdup required to maintain a fairly constant discharge temperature throughout the day.

Table 12-5 presents typical values of solar radiation on a horizontal surface, Btu/(h·ft^2), based on analysis of Weather Bureau records for a number of stations throughout the United States. These are clear-day values, rarely exceeded even in the high arid regions. The normal or actual average monthly values are only 50 to 60 percent of the tabulated figures for most of the eastern United States and 80 to 90 percent in the arid southwest. Also, the solar radiation should be multiplied by the absorption coefficient for the pond, which appears to exceed 95 percent.

SOLIDS-DRYING FUNDAMENTALS*

General References: Cook and DuMont, *Process Drying Practice,* McGraw-Hill, 1991. *Drying Technology—An International Journal,* Marcel Dekker, N.Y., 1982. Hall, *Dictionary of Drying,* Marcel Dekker, N.Y., 1979. Keey, *Introduction to Industrial Drying Operations,* Pergamon, N.Y., 1978. Masters, *Spray Drying Handbook,* Wiley, N.Y., 1990. Mujumdar, *Handbook of Industrial Drying,* Marcel Dekker, N.Y., 1987. Nonhebel and Moss, *Drying of Solids in the Chemical Industry,* CRC Press, Ohio, 1971. van't Land, *Industrial Drying Equipment,* Marcel Dekker, N.Y., 1991.

INTRODUCTION

The material on solids drying is divided into two subsections, "Solids-Drying Fundamentals," and "Solids-Drying Equipment." In this introductory part some elementary definitions are given. In solids-gas contacting equipment, the solids bed can exist in any of the following four conditions.

Static This is a dense bed of solids in which each particle rests upon another at essentially the settled bulk density of the solids phase. Specifically, *there is no relative motion among solids particles* (Fig. 12-26).

Moving This is a slightly expanded bed of solids in which the particles are separated only enough to flow one over another. Usually the flow is downward under the force of gravity, but upward motion by mechanical lifting or agitation may also occur within the process vessel. In some cases, lifting of the solids is accomplished in separate equipment, and solids flow in the presence of the gas phase is downward only. The latter is a moving bed as usually defined in the petroleum industry. In this definition, *solids motion is achieved by either mechanical agitation or gravity force* (Fig. 12-27).

Fluidized This is an expanded condition in which the solids particles are supported by drag forces caused by the gas phase passing through the interstices among the particles at some critical velocity. It is an unstable condition in that the superficial gas velocity upward is less than the terminal setting velocity of the solids particles; the gas velocity is not sufficient to entrain and convey continuously all the solids. At the same time, there exist, within the stream of gas, eddies traveling at high enough velocities to lift the particles temporarily. Particle motion is continually upward and falling back. Specifically, the solids phase and the gas phase are intermixed and *together behave like a boiling fluid* (Fig. 12-28).

Dilute This is a fully expanded condition in which the solids particles are so widely separated that they exert essentially no influence upon each other. Specifically, the solids phase is so fully dispersed in the gas that *the density of the suspension is essentially that of the gas phase alone* (Fig. 12-29). Commonly, this situation exists when the gas velocity at all points in the system exceeds the terminal settling velocity of the solids and the particles can be lifted and continuously conveyed by the gas; however, this is not always true. Gravity settling chambers such as prilling towers and countercurrent-flow spray dryers are two exceptions in which gas velocity is insufficient to entrain the solids completely.

Gas-Solids Contacting Terms used in this section to describe the method by which gas may contact a bed of solids are the following:

1. *Parallel flow.* The direction of gas flow is parallel to the surface of the solids phase. Contacting is primarily at the interface between phases, with possibly some penetration of gas into the voids among the solids near the surface. The solids bed is usually in a static condition (Fig. 12-30).

FIG. 12-26 Solids bed in static condition (tray dryer).

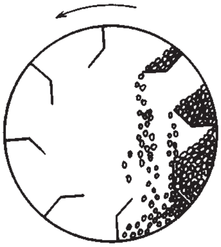

FIG. 12-27 Moving solids bed in a rotary dryer with lifters.

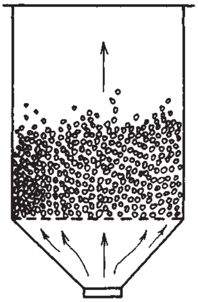

FIG. 12-28 Fluidized solids bed.

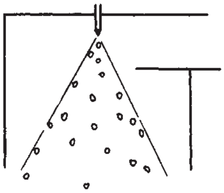

FIG. 12-29 Solids in a dilute condition near the top of a spray dryer.

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* The contribution of George A. Schurr, E. I. du Pont de Nemours & Co., to material that was used from the sixth edition is acknowledged. (Solids Drying)

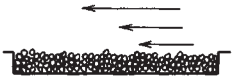

FIG. 12-30 Parallel gas flow over a static bed of solids.

2. *Perpendicular flow.* The direction of gas flow is normal to the phase interface. The gas impinges on the solids bed. Again the solids bed is usually in a static condition (Fig. 12-31).

3. *Through circulation.* The gas penetrates and flows through interstices among the solids, circulating more or less freely around the individual particles (Fig. 12-32). This may occur when solids are in static, moving, fluidized, or dilute conditions.

Three additional terms require definition.

1. *Cocurrent gas flow.* The gas phase and solids particles both flow in the same direction (Fig. 12-33).

2. *Countercurrent gas flow.* The direction of gas flow is exactly opposite to the direction of solids movement.

3. *Cross-flow of gas.* The direction of gas flow is at a right angle to that of solids movement, across the solids bed (Fig. 12-34).

Because in a gas-solids-contacting operation heat transfer and mass transfer take place at the solids' surfaces, maximum process efficiency can be expected with a maximum exposure of solids surface to the gas phase, together with thorough mixing of gas and solids. Both are important. Within any arrangement of particulate solids, gas is present in the voids among the particles and contacts all surfaces except at the points of particle contact. When the solids bed is in a static or slightly moving condition, however, gas within the voids is cut off from the main body of the gas phase. Some transfer of energy and mass may occur by diffusion, but it is usually insignificant.

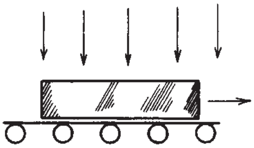

FIG. 12-31 Circulating gas impinging on a large solid object in perpendicular flow, in a roller-conveyor furnace.

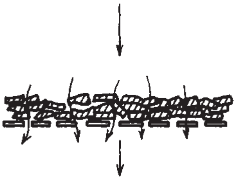

FIG. 12-32 Gas passing through a bed of preformed solids, in through circulation on a perforated-apron conveyor.

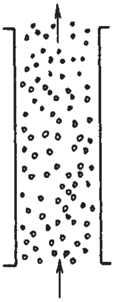

FIG. 12-33 Cocurrent gas-solids flow in a vertical-lift dilute-phase pneumatic conveyor.

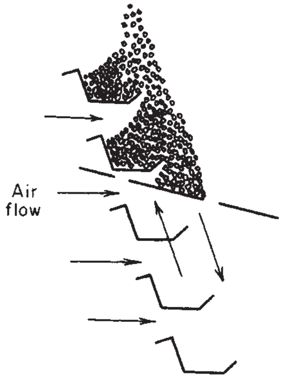

FIG. 12-34 Cross-flow of gas and solids in a cascade-type gravity dryer. (*Link-Belt Co., Multi-Louvre principle.*)

Equipment design and selection are governed by two factors:

1. Mechanical considerations
2. Solids flow and surface characteristics.

The former usually involves process temperature or isolation. Solids surface characteristics are important in that they control the extent to which an operation is diffusion-limited, i.e., diffusion into and out of the pores of a given solids particle, not through the voids among separate particles. The size of the solids particles, the surface-to-mass ratio, is also important in the evaluation of surface characteristics and the diffusion problem.

Gas-Solids Separations After the solids and gas have been brought together and mixed in a gas-solids contactor, it becomes necessary to separate the two phases. If the solids are sufficiently coarse and the gas velocity sufficiently low, it is possible to effect a complete gravitational separation in the primary contactor. Applications of this type are rare, however, and supplementary dust-collection equipment is commonly required. The recovery step may even dictate the type of primary contacting device selected. For example, when treating an extremely friable solid material, a deep fluidized-solids contactor might overload the collection system with fines, whereas the more gentle contacting of a traveling-screen contactor would be expected to produce a minimum of fines by attrition. Therefore, although gas-solids separation is usually considered as separate and distinct from the primary contacting operation, it is usually desirable to evaluate the separation problem at the same time that contacting methods are evaluated.

Definitions Drying generally refers to the removal of a liquid from a solid by **evaporation.** Mechanical methods for separating a liquid from a solid are not generally considered drying, although they often precede a drying operation, since it is less expensive and frequently easier to use mechanical methods than to use thermal methods.

This subsection presents the theory and fundamental concepts of the drying of solids.

Equipment commonly employed for the drying of solids is described both in this subsection in Sec. 12, where indirect heat transfer devices are discussed, and in Sec. 17 where fluidized beds are covered. Dryer control is discussed in Sec. 8. Excluding fluid beds this subsection contains mainly descriptions of direct-heat-transfer equipment. It also includes some indirect units; e.g., vacuum dryers, furnaces, steam-tube dryers, and rotary calciners.

Generally accepted terminology and definitions are given alphabetically in the following paragraphs.

Bound moisture in a solid is that liquid which exerts a vapor pressure less than that of the pure liquid at the given temperature. Liquid may become bound by retention in small capillaries, by solution in cell or fiber walls, by homogeneous solution throughout the solid, and by chemical or physical adsorption on solid surfaces.

Capillary flow is the flow of liquid through the interstices and over the surface of a solid, caused by liquid-solid molecular attraction.

Constant-rate period is that drying period during which the rate of water removal per unit of drying surface is constant.

Critical moisture content is the average moisture content when the constant-rate period ends.

Dry-weight basis expresses the moisture content of wet solid as kilograms of water per kilogram of bone-dry solid.

Equilibrium moisture content is the limiting moisture to which a given material can be dried under specific conditions of air temperature and humidity.

Falling-rate period is a drying period during which the instantaneous drying rate continually decreases.

Fiber-saturation point is the moisture content of cellular materials (e.g., wood) at which the cell walls are completely saturated while the cavities are liquid-free. It may be defined as the equilibrium moisture content as the humidity of the surrounding atmosphere approaches saturation.

Free-moisture content is that liquid which is removable at a given temperature and humidity. It may include bound and unbound moisture.

Funicular state is that condition in drying a porous body when capillary suction results in air being sucked into the pores.

Hygroscopic material is material that may contain bound moisture.

Initial moisture distribution refers to the moisture distribution throughout a solid at the start of drying.

Internal diffusion may be defined as the movement of liquid or vapor through a solid as the result of a concentration difference.

Moisture content of a solid is usually expressed as moisture quantity per unit weight of the dry or wet solid.

Moisture gradient refers to the distribution of water in a solid at a given moment in the drying process.

Nonhygroscopic material is material that can contain no bound moisture.

Pendular state is that state of a liquid in a porous solid when a continuous film of liquid no longer exists around and between discrete particles so that flow by capillary cannot occur. This state succeeds the funicular state.

Unaccomplished moisture change is the ratio of the free moisture present at any time to that initially present.

Unbound moisture in a hygroscopic material is that moisture in excess of the equilibrium moisture content corresponding to saturation humidity. All water in a nonhygroscopic material is unbound water.

Wet-weight basis expresses the moisture in a material as a percentage of the weight of the wet solid. Use of a dry-weight basis is recommended since the percentage change of moisture is constant for all moisture levels. When the wet-weight basis is used to express moisture content, a 2 or 3 percent change at high moisture contents (above 70 percent) actually represents a 15 to 20 percent change in evaporative load. See Fig. 12-35 for the relationship between the dry- and wet-weight bases.

APPLICATION OF PSYCHROMETRY TO DRYING

In any drying process, if an adequate supply of heat is assumed, the temperature and rate at which liquid vaporization occurs will depend on the vapor concentration in the surrounding atmosphere.

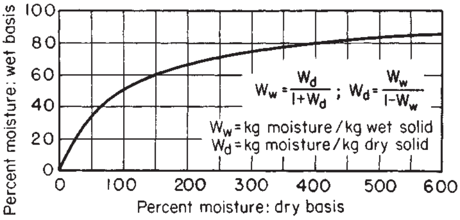

FIG. 12-35 Relationship between wet-weight and dry-weight bases.

In vacuum drying or other processes containing atmospheres of 100 percent vapor, the temperature of liquid vaporization will equal or exceed the saturation temperature of the liquid at the system pressure. (When a free liquid or wetted surface is present, drying will occur at the saturation temperature, just as free water at 101.325 kPa vaporizes in a 100 percent steam atmosphere at 100°C.)

On the other hand, when evolved vapor is purged from the dryer environment by using a second (inert) gas, the temperature at which vaporization occurs will depend on the concentration of vapor in the surrounding gas. In effect, the liquid must be heated to a temperature at which its vapor pressure equals or exceeds the partial pressure of vapor in the purge gas. In the reverse situation, condensation will occur.

In most drying operations, water is the liquid evaporated and air is the normally employed purge gas. For drying purposes, a psychrometric chart found very useful is that reproduced in Fig. 12-36.

1. The **wet-bulb or saturation temperature line** gives the maximum weight of water vapor that 1 kg of dry air can carry at the intersecting **dry-bulb temperature** shown on the abscissa at saturation humidity. The partial pressure of water in air equals the water-vapor pressure at that temperature. The saturation humidity is defined by

$$H_s = p_s/(P - p_s)18/28.9 \tag{12-17}$$

where H_s = saturation humidity (kg/kg dry air), p_s = vapor pressure of water at temperature t_s, P = absolute pressure, and 18/28.9 = ratio of molecular weights of water (18) and air (28.9). Similarly, the humidity at any condition less than saturation is given by

$$H = p/(P - p)18/28.9 \tag{12-18}$$

2. The percent relative humidity is defined by

$$H_R = 100(p/p_s) \tag{12-19}$$

where p = partial pressure of water vapor in the air, p_s = vapor pressure of water at the same temperature, and H_R = percent relative humidity.

3. Humid volumes are given by the curves entitled "Volume m^3/kg dry air." The volumes are plotted as functions of absolute humidity and temperature. The difference between dry-air specific volume and humid-air volume at a given temperature is the volume of water vapor.

4. Enthalpy data are given on the basis of kilojoules per kilogram of dry air. **Enthalpy-at-saturation data** are accurate only at the saturation temperature and humidity. Enthalpy deviation curves permit enthalpy corrections for humidities less than saturation and show how the wet-bulb-temperature lines do not precisely coincide with constant-enthalpy, adiabatic cooling lines.

5. There are no lines for humid heats on Fig. 12-36. These may be calculated by

$$C_s = 1.0 + 1.87H \tag{12-20}$$

where C_s = humid heat of moist air, kJ/(kg·K); 1.0 = specific heat of dry air, kJ/(kg·K), 1.87 = specific heat of water vapor, kJ/(kg·K); and H = absolute humidity, kg/kg dry air.

6. The wet-bulb-temperature lines represent also the adiabatic-saturation lines for air and water vapor only. These are based on the relationship

$$H_s - H = (C_s/\lambda)(t - t_s) \tag{12-21}$$

where H_s and t_s = adiabatic saturation humidity and temperature respectively, corresponding to the air conditions represented by H and t, and C_s = humid heat for humidity H. The slope of the adiabatic-saturation curve is C_s/λ, where λ = latent heat of evaporation at t_s. These lines show the relationship between the temperature and humidity of air passing through a continuous dryer operating adiabatically.

The wet-bulb temperature is established by a dynamic equilibrium between heat and mass transfer when liquid evaporates from a small mass, such as the wet bulb of a thermometer, into a very large mass of gas such that the latter undergoes no temperature or humidity change. It is expressed by the relationship

$$h_c(t - t_w) = k'_g\lambda(H_w - H_a) \tag{12-22}$$

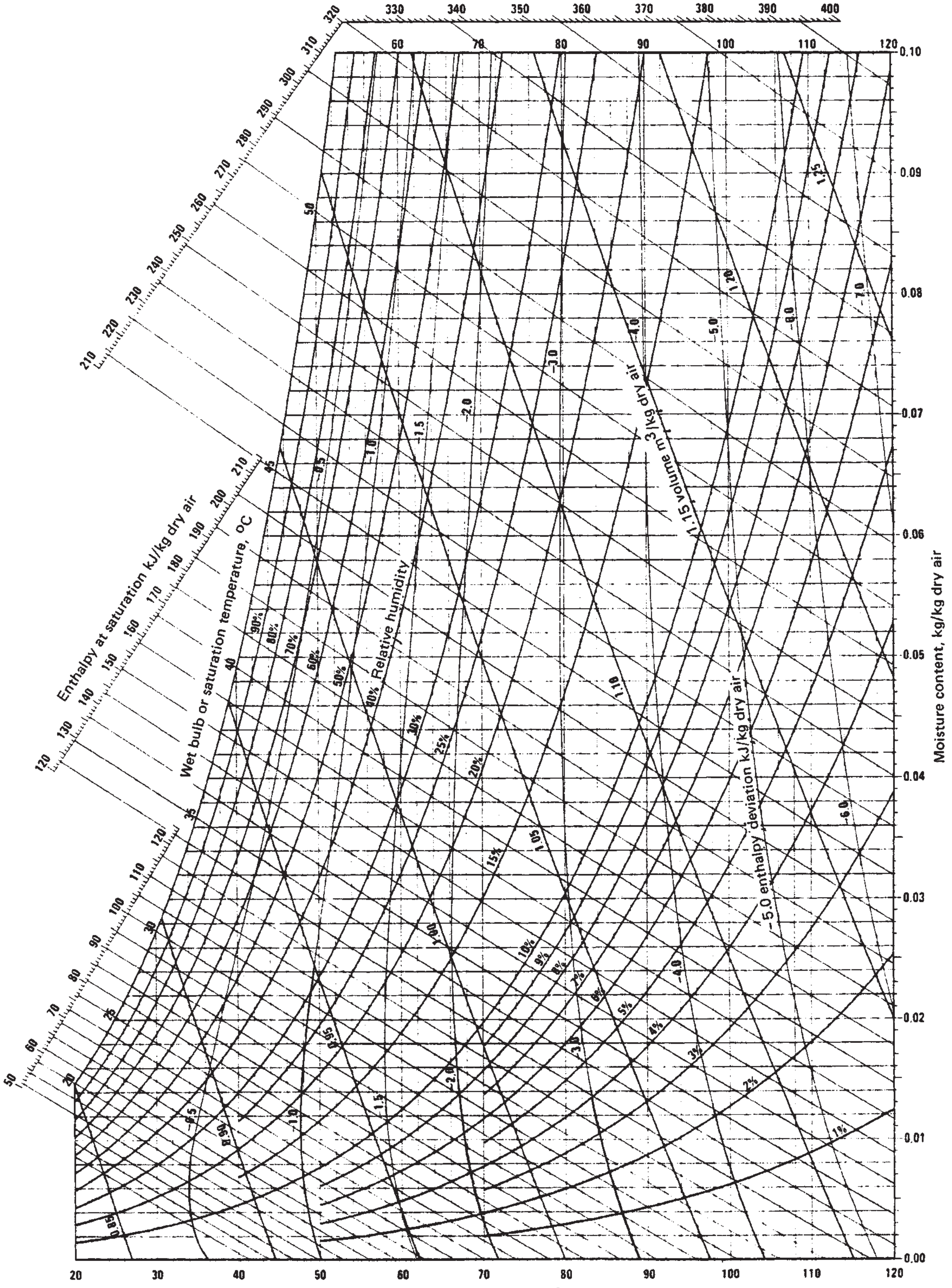

FIG. 12-36 Psychrometric chart: properties of air and water-vapor mixtures from 20 to 120°C. (*Carrier Corp.*)

where h_c = heat-transfer coefficient by convection, J/(m^2·s·K) [Btu/(h·ft^2·°F)]; t = air temperature, K; t_w = wet-bulb temperature of air, K; k'_g = mass-transfer coefficient, kg/(s·m^2) (kg/kg) [lb/(h·ft^2)(lb/lb)]; λ = latent heat of evaporation at t_w, J/kg (Btu/lb); H_w = saturated humidity at t_w = kg/kg of dry air; and H_a = humidity of the surrounding air, kg/kg of dry air.

For air–water-vapor mixtures, it so happens that $h_c/k'_g = C_s$ approximately, although there is no theoretical reason for this. Hence, since the ratio $(H_w - H_a)/(t_w - t)$ equals $h_c/k'_g/\lambda$, which represents the slope of the wet-bulb-temperature lines, it is also equal to C_s/λ, the slope of the adiabatic-saturation lines as shown previously.

A given humidity chart is precise only at the pressure for which it is evaluated. Most air–water-vapor charts are based on a pressure of 1 atm. Humidities read from these charts for given values of wet- and dry-bulb temperature apply only at an atmospheric pressure of 760 mmHg. If the total pressure is different from 760 mmHg, the humidity at a given wet-bulb and dry-bulb temperature must be corrected according to the following relationship.

$$H_a = H_o + 0.622p_w\left(\frac{1}{P - p_w} - \frac{1}{760 - p_w}\right) \qquad (12\text{-}23)$$

where H_a = humidity of air at pressure P, kg/kg of dry air; H_o = humidity of air as read from a humidity chart based on 760-mm pressure at the observed wet- and dry-bulb temperatures, kg/kg dry air, p_w = vapor pressure of water at the observed wet-bulb temperature, mmHg; and P = the pressure at which the wet- and dry-bulb readings were taken. Similar corrections can be derived to correct specific volume, the saturation-humidity curve, and the relative-humidity curves.

HUMIDITY CHARTS FOR SOLVENT VAPORS

Humidity charts for other solvent vapors may be prepared in an analogous manner. There is one important difference involved, however, in that the wet-bulb temperature differs considerably from the adiabatic-saturation temperatures for vapors other than water.

Figures 12-37 to 12-39 show humidity charts for carbon tetrachloride, benzene, and toluene. The lines on these charts have been calculated in the manner outlined for air–water vapor except for the wet-bulb-temperature lines. The determination of these lines depends on data for the psychrometric ratio h_c/k'_g, as indicated by Eq. (12-22). For the charts shown, the wet-bulb-temperature lines are based on the following equation:

$$H_w - H = (\alpha h_c/\lambda_w k'_g)(t - t_w) \qquad (12\text{-}24)$$

where α = radiation correction factor, a value of 1.06 having been used for these charts. Values of h_c/k'_g, obtained from values of h_c/k'_gC_s as presented by Walker, Lewis, McAdams, and Gilliland (*Principles of Chemical Engineering*, 3d ed., McGraw-Hill, New York, 1937), where C_s = humid heat of air with respect to the vapor involved, are as follows:

Material	Carbon tetrachloride	Benzene	Toluene
h_c/k'_gC_s	0.51	0.54	0.47

A discussion of the theory of the relationship between h_c and k'_g may be found in the psychrometry part of this section. Because both theoretical and experimental values of h_c/k'_g apply only to dilute gas mixtures, the wet-bulb lines at high concentrations have been omitted. For a discussion of the precautions to be taken in making psychrometric determinations of solvent vapors at low solvent wet-bulb temperatures in the presence of water vapor, see the paper by Sherwood and Comings [*Trans. Am. Inst. Chem. Eng.*, **28,** 88 (1932)].

GENERAL CONDITIONS FOR DRYING

Solids drying encompasses two fundamental and simultaneous processes: (1) heat is transferred to evaporate liquid, and (2) mass is

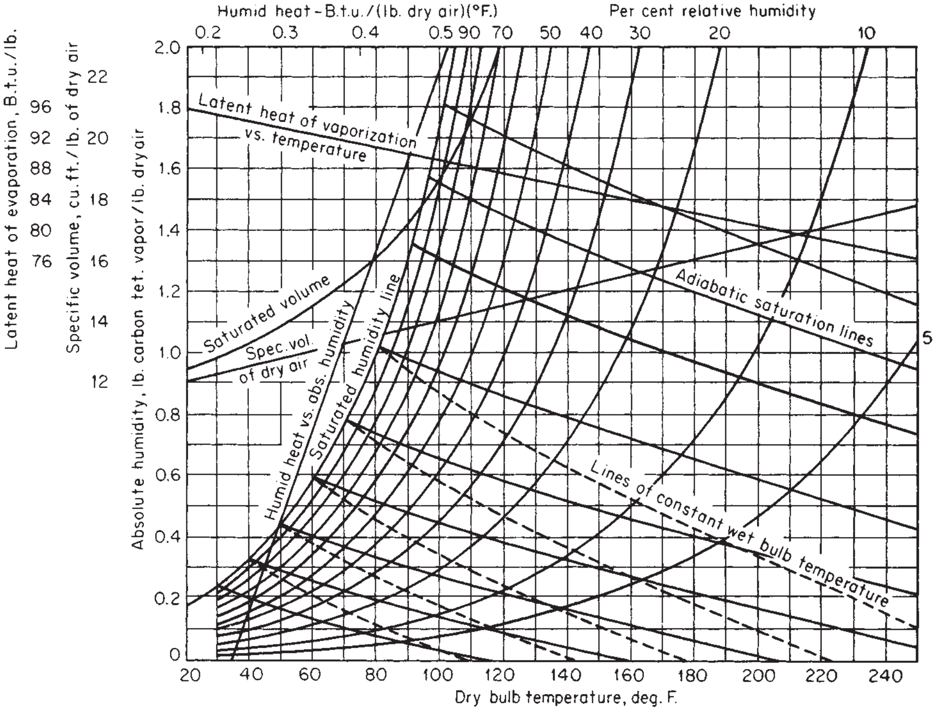

FIG. 12-37 Humidity chart for air-carbon tetrachloride vapor mixture. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

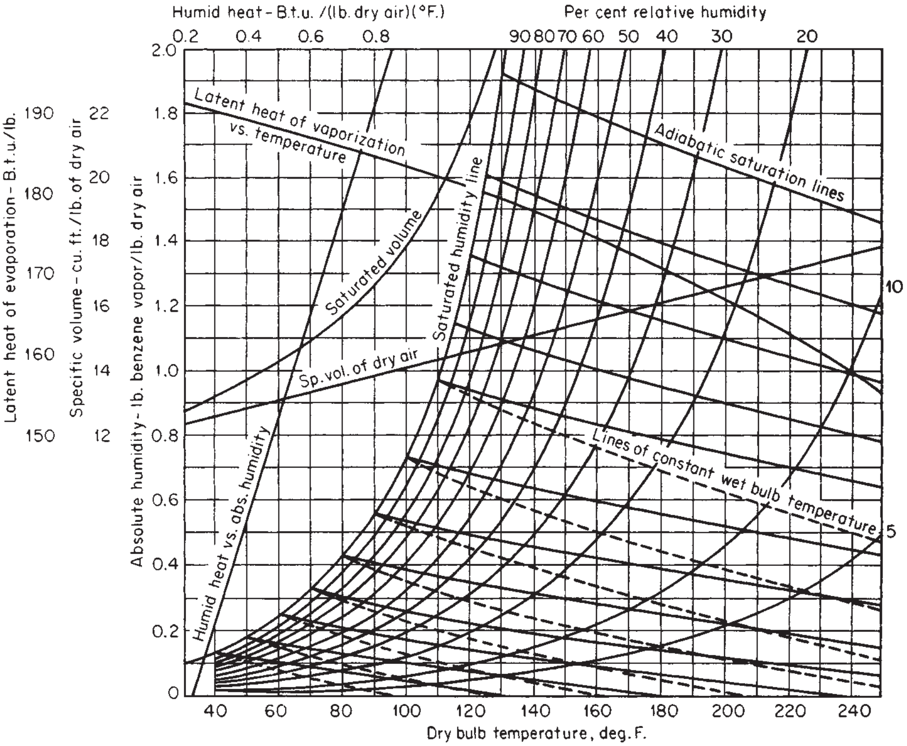

FIG. 12-38 Humidity chart for air-benzene-vapor mixture. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

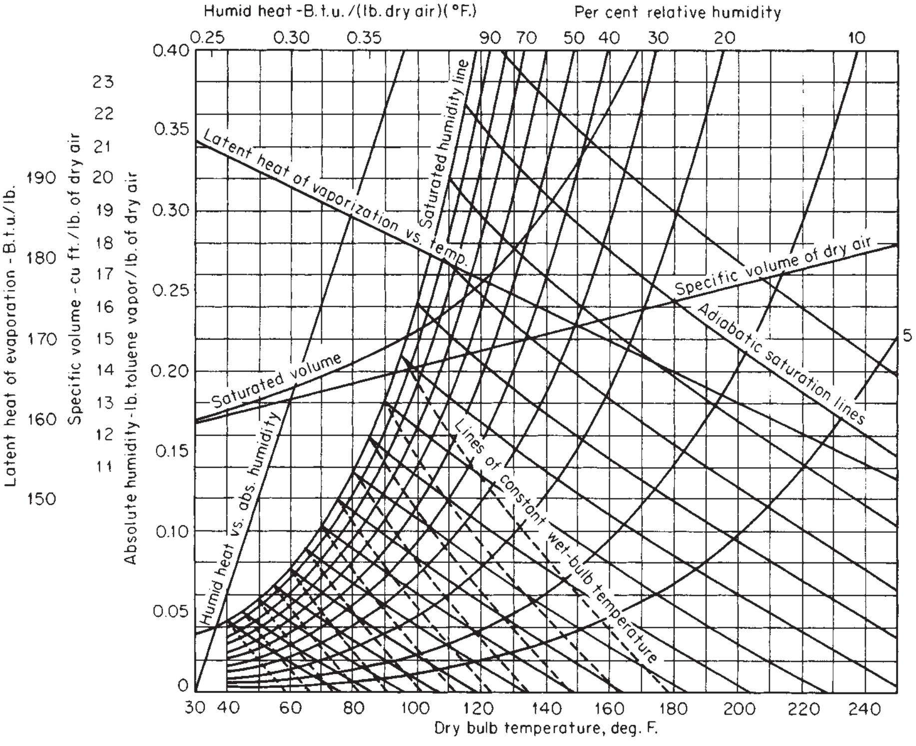

FIG. 12-39 Humidity chart for air-toluene-vapor mixture. To convert British thermal units per pound to joules per kilogram, multiply by 2326; to convert British thermal units per pound dry air-degree Fahrenheit to joules per kilogram-kelvin, multiply by 4186.8; and to convert cubic feet per pound to cubic meters per kilogram, multiply by 0.0624.

transferred as a liquid or vapor within the solid and as a vapor from the surface. The factors governing the rates of these processes determine the drying rate.

Commercial dryers differ fundamentally by the methods of heat transfer employed (see classification of dryers, Fig. 12-45). These industrial-dryer operations may utilize heat transfer by convection, conduction, radiation, or a combination of these. In each case, however, heat must flow to the outer surface and then into the interior of the solid. The single exception is dielectric and microwave drying, in which high-frequency electricity generates heat internally and produces a high temperature within the material and on its surface.

Mass is transferred in drying as a liquid and vapor within the solid and as vapor from the exposed surfaces. Movement within the solid results from a concentration gradient which is dependent on the characteristics of the solid. A solid to be dried may be porous or nonporous. It can also be hygroscopic or nonhygroscopic. Many solids fall intermediately between these two extremes, but it is generally convenient to consider the solid to be one or the other.

A study of how a solid dries may be based on the **internal** mechanism of liquid flow or on the effect of the **external** conditions of temperature, humidity, air flow, state of subdivision, etc., on the drying rate of the solids. The former procedure generally requires a fundamental study of the internal condition. The latter procedure, although less fundamental, is more generally used because the results have greater immediate application in equipment design and evaluation.

INTERNAL MECHANISM OF LIQUID FLOW

The structure of the solid determines the mechanism for which internal liquid flow may occur. These mechanisms can include (1) **diffusion** in continuous, homogeneous solids, (2) **capillary flow** in granular and porous solids, (3) flow caused by **shrinkage** and **pressure** gradients, (4) flow caused by **gravity,** and (5) flow caused by a **vaporization-condensation** sequence.

In general, one mechanism predominates at any given time in a solid during drying, but it is not uncommon to find different mechanisms predominating at different times during the drying cycle.

The study of internal moisture gradients establishes the particular mechanism which controls during the drying of a solid. The experimental determination of reliable moisture gradients is extremely difficult.

Hougen, McCauley, and Marshall [*Trans. Am. Inst. Chem. Eng.*, **36,** 183 (1940)] discussed the conditions under which capillary and diffusional flow may be expected in a drying solid and analyzed the published experimental moisture-gradient data for the two cases. Their curves indicate that capillary flow is typified by a moisture gradient involving a double curvature and point of inflection (Fig. 12-40*a*) while diffusional flow is a smooth curve, concave downward (Fig. 12-40*b*), as would be predicted from the diffusion equations. They also showed that the liquid-diffusion coefficient is usually a function of moisture content which decreases with decreasing moisture. The effect of variable diffusivity is illustrated in Fig. 12-40*b*, where the dashed line is calculated for constant diffusivity and the solid line is experimental for the case in which the diffusion coefficient is moisture-dependent. Thus, the integrated diffusion equations assuming constant diffusivity only approximate the actual behavior.

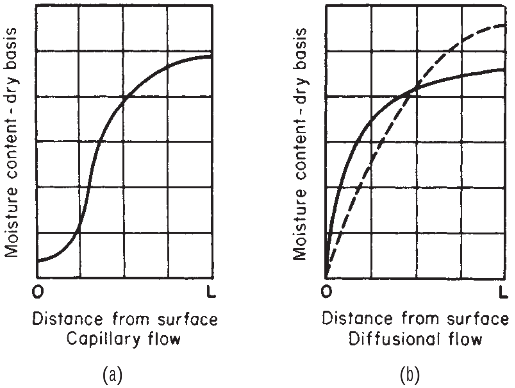

FIG. 12-40 Two types of internal moisture gradients obtained in drying solids.

These authors classified solids on the basis of capillary and diffusional flow:

Capillary Flow Moisture which is held in the interstices of solids, as liquid on the surface, or as free moisture in cell cavities, moves by gravity and capillarity, provided that passageways for continuous flow are present. In drying, liquid flow resulting from capillarity applies to liquids not held in solution and to all moisture above the fiber-saturation point, as in textiles, paper, and leather, and to all moisture above the equilibrium moisture content at atmospheric saturations, as in fine powders and granular solids, such as paint pigments, minerals, clays, soil, and sand.

Vapor Diffusion Moisture may move by vapor diffusion through the solid, provided that a temperature gradient is established by heating, thus creating a vapor-pressure gradient. Vaporization and vapor diffusion may occur in any solid in which heating takes place at one surface and drying from the other and in which liquid is isolated between granules of solid.

Liquid Diffusion The movement of liquids by diffusion in solids is restricted to the equilibrium moisture content below the point of atmospheric saturation and to systems in which moisture and solid are mutually soluble. The first class applies to the last stages in the drying of clays, starches, flour, textiles, paper, and wood; the second class includes the drying of soaps, glues, gelatins, and pastes.

External Conditions The principal external variables involved in any drying study are temperature, humidity, air flow, state of subdivision of the solid, agitation of the solid, method of supporting the solid, and contact between hot surfaces and wet solid. All these variables will not necessarily occur in one problem.

PERIODS OF DRYING

When a solid is dried experimentally, data relating moisture content to time are usually obtained. These data are then plotted as moisture content (dry basis) W versus time θ, as shown in Fig. 12-41*a*. This curve represents the general case when a wet solid loses moisture first by evaporation from a saturated surface on the solid, followed in turn by a period of evaporation from a saturated surface of gradually decreasing area, and, finally, when the latter evaporates in the interior of the solid.

Figure 12-41*a* indicates that the drying rate is subject to variation with time or moisture content. This variation is better illustrated by graphically or numerically differentiating the curve and plotting $dW/d\theta$ versus W, as shown in Fig. 12-41*b*, or as $dW/d\theta$ versus θ, as shown in Fig. 12-41*c*. These **rate curves** illustrate that the drying process is not a smooth, continuous one in which a single mechanism controls throughout. Figure 12-41*c* has the advantage of showing how long each drying period lasts.

The section AB on each curve represents a **warming-up** period of the solids. Section BC on each curve represents the **constant-rate** period. Point C, where the constant rate ends and the drying rate begins falling, is termed the **critical-moisture** content. The curved portion CD on Fig. 12-41*a* is termed the **falling-rate** period and, as shown in Fig. 12-41*b* and *c*, is typified by a continuously changing rate throughout the remainder of the drying cycle. Point E (Fig. 12-41*b*) represents the point at which all the exposed surface becomes completely unsaturated and marks the start of that portion of the drying cycle during which the rate of internal moisture movement controls the drying rate. Portion CE in Fig. 12-41*b* is usually defined as the first falling-rate drying period; portion DE, as the second falling-rate period.

Constant-rate Period In the constant-rate period moisture movement within the solid is rapid enough to maintain a saturated condition at the surface, and the rate of drying is controlled by the rate of heat transferred to the evaporating surface. Drying proceeds by diffusion of vapor from the saturated surface of the material across a

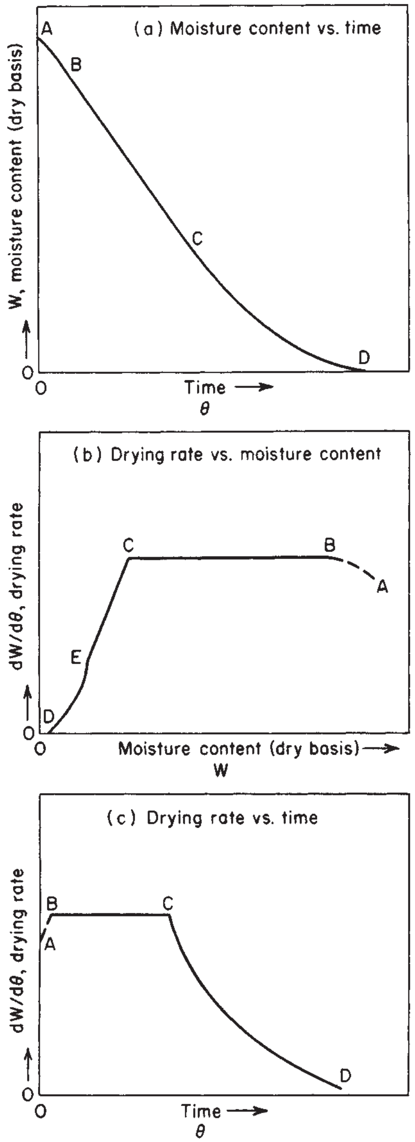

FIG. 12-41 The periods of drying.

stagnant air film into the environment. The rate of mass transfer balances the rate of heat transfer, and the temperature of the saturated surface remains constant. The mechanism of moisture removal is equivalent to evaporation from a body of water* and is essentially independent of the nature of the solids.

If heat is transferred solely by convection and in the absence of other heat effects, the surface temperature approaches the wet-bulb temperature. However, when heat is transferred by radiation, convection, or a combination of these and convection, the temperature at the saturated surface is between the wet-bulb temperature and the boiling point of water. Under these conditions, the rate of heat transfer is increased and a higher drying rate results.

When heat is transferred to a wet solid by convection to hot surfaces and heat transfer by convection is negligible, the solids approach the boiling-point temperature rather than the wet-bulb temperature. This method of heat transfer is utilized in indirect dryers (see classification of dryers in Fig. 12-45). Radiation is also effective in increasing the constant rate by augmenting the convection heat transfer and raising the surface temperature above the wet-bulb temperature.

When the heat for evaporation in the constant-rate period is supplied by a hot gas, a dynamic equilibrium establishes the rate of heat transfer to the material and the rate of vapor removal from the surface:

$$dw/d\theta = h_t A\,\Delta t/\lambda = k_g A\,\Delta p \tag{12-25}$$

where $dw/d\theta$ = drying rate, kg water/s; h_t = total heat-transfer coefficient, J/(m^2·s·K) [Btu/(h·ft^2·°F)]; A = area for heat transfer and evaporation, m^2; λ = latent heat of evaporation at t_s', J/kg (Btu/lb); k_g = mass-transfer coefficient, kg/(s·m^2·atm) [(lb/(h·ft^2·atm)]; $\Delta t = t - t_s'$, where t = gas (dry-bulb) temperature, K; $p = p_s - p$, where p_s = vapor pressure of water at surface temperature t_s', atm; and p = partial pressure of water vapor in the gas, atm.

The magnitude of the constant rate depends upon three factors:

1. The heat- or mass-transfer coefficient
2. The area exposed to the drying medium
3. The difference in temperature or humidity between the gas stream and the wet surface of the solid

All these factors are the external variables. The internal mechanism of liquid flow does not affect the constant rate.

For drying calculations, it is convenient to express Eq. (12-25) in terms of the decrease in moisture content rather than in the quantity of water evaporated. For evaporation from a tray of wet material, if no change in volume during drying is assumed, Eq. (12-25) becomes

$$dw/d\theta = (h/\rho_s\, d\lambda)(t - t_s') \tag{12-26}$$

where $dw/d\theta$ = drying rate, kg water/(s·kg dry solids); h_t = total heat-transfer coefficient, J/(m^2·s·K) [Btu/(h·ft^2·°F)]; ρ_s = bulk density dry material, kg/m^3; d = thickness of bed, m; λ = latent heat of vaporization, J/kg (Btu/lb); t = air temperature, K; and t_s' = evaporating surface temperature, K. (Note that $dw/d\theta$ is inherently negative.)

A similar equation can be written for the through-circulation case:

$$dW/d\theta = (h_t a/\rho_s \lambda(t - t_s') \tag{12-27}$$

where a = m^2 of heat-transfer area/m^3 of bed, 1/m; and other symbols are as in Eq. (12-26).

The values of ρ_s and/or a must be known in order to use Eqs. (12-26) and (12-27). The value of a is difficult to estimate without experimental data. When the void fraction is known, a can sometimes be estimated from the following relationships:

For spherical particles,

$$a = \frac{6(1-F)}{(D_p)_m} \tag{12-28}$$

For uniform cylindrical particles,

$$a = \frac{4(0.5D_0 + Z)(1-F)}{D_0 Z} \tag{12-29}$$

where F = void fraction; $(D_p)_m$ = harmonic mean diameter of spherical particles, m; D_0 = diameter of cylinder, m; and Z = height of cylinder, m. For cylindrical particles that are long relative to their diameter, the term $0.5D_0$ in Eq. (12-29) can be neglected.

Falling-rate Period The falling-rate period begins at the critical moisture content when the constant-rate period ends. When the falling moisture content is above the critical moisture content, the whole drying process will occur under constant-rate conditions. If, on the other hand, the initial moisture content is below the critical moisture content, the entire drying process will occur in the falling-rate period. This period is usually divided into two zones: (1) the zone of **unsaturated surface drying** and (2) the zone where **internal moisture movement** controls. In the first zone, the entire evaporating surface can no longer be maintained and saturated by moisture movement within the solid. The drying rate decreases from the unsaturated portion, and hence the rate for the total surface decreases. Generally, the drying rate depends on factors affecting the diffusion of moisture away from the evaporating surface and those affecting the rate of internal moisture movement.

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* The term "water" is used for convenience; this discussion applies equally to other liquids.

As drying proceeds, the point is reached where the evaporating surface is unsaturated. The point of evaporation moves into the solid, and the dry process enters the second falling-rate period. The drying rate is now governed by the rate of internal moisture movement; the influence of external variables diminishes. This period usually predominates in determining the overall drying time to lower moisture content.

LIQUID DIFFUSION

Diffusion-controlled mass transfer is assumed when the vapor or liquid flow conforms to Fick's second law of diffusion. This is stated in the unsteady-state-diffusion equation using mass-transfer notation as

$$\delta c/\delta\theta = D_{AB}(\delta^2 C/dx) \qquad (12\text{-}30)$$

where c = concentration of one component in a two-component phase of A and B, θ = diffusion time, x = distance in the direction of diffusion, and D_{AB} = binary diffusivity of the phase AB. This equation applies to diffusion in solids, stationary liquids, and stagnant gases.

The diffusion equation for the falling-rate drying period for a slab can be derived from the diffusion equation if one assumes that the surface is dry or at an equilibrium moisture content and that the initial moisture distribution is uniform. For these conditions, the following equation is obtained:

$$\frac{W - W_e}{W_c - W_e} = \frac{8}{\pi^2}\left[\sum_{n=0}^{n=\infty} \frac{1}{(2n+1)}\, e^{-(2n+1)^2 D_\ell \theta (\pi/2d)^2}\right] \qquad (12\text{-}31)$$

where W, W_e, and W_c = average moisture content (dry basis) at any time, θ, at the start of the falling-rate period and in equilibrium with the environment respectively, kg/kg; D_ℓ = liquid diffusivity, m²/s; θ = time from start of falling-rate period, s; and d = one-half of the thickness of the solid layer through which diffusion occurs, m. When evaporation occurs from only one face, d = total thickness, m.

Equation (12-31) assumes that D_ℓ is constant; however, D_ℓ is rarely constant but varies with moisture content, temperature, and humidity. For long drying times, Eq. (12-31) simplifies to a limiting form of the diffusion equation as

$$\frac{W - W_e}{W_c - W_e} = \frac{8}{\pi^2}\left[e^{-D_\ell \theta (\pi/2d)^2}\right] \qquad (12\text{-}32)$$

Equation (12-32) may be differentiated to give the drying rate as

$$-\frac{dW}{d\theta} = \frac{\pi^2 D_\ell}{4d^2}(W - W_e) \qquad (12\text{-}33)$$

where $dW/d\theta$ = drying rate, kg/s.

When Eq. (12-31) is plotted on semilogarithmic graph paper, a straight line is obtained for values of $(W - W_e)/(W_c - W_e) < 0.6$. It is in the straight-line portion that the approximate form [Eq. (12-33)] applies.

Equations (12-31), (12-32), and (12-33) hold only for a slab-sheet solid whose thickness is small relative to the other two dimensions. For other shapes, reference should be made to Crank (*The Mathematics of Diffusion*, Oxford, London, 1956).

An approximate equation for the falling-rate period may be obtained by integration of Eq. (12-33). This gives an equation for materials in which moisture movement is controlled by diffusion:

$$\theta_f = \frac{4d^2}{D_\ell \pi^2} \ln \frac{W_c - W_e}{W - W_e} \qquad (12\text{-}34)$$

where θ_f = drying time in the falling-rate period.

Diffusion equations may also be used to study vapor diffusion in porous materials. It should be clear that all estimates based on relationships that assume constant diffusivity are approximations. Liquid diffusivity in solids usually decreases with moisture concentration. Liquid and vapor diffusivity also change, and material shrinks during drying.

CAPILLARY THEORY

If the porous size of a granular material is suitable, moisture may move from a region of high to one of low concentration as the result of capillary action rather than by diffusion. The capillary theory assumes that a bed of nonporous spheres is composed of particles surrounding a space called a pore. These pores are connected by passages of various sizes. As water is progressively removed from the bed, the curvature of the water surface in the interstices of the top layer of spheres increases and a suction pressure resulting from curvature is set up. As the removal of water continues, the suction pressure attains a value in which air is drawn into the pore spaces between successive layers of spheres.

This entry suction or suction potential is a measure of the resultant forces tending to draw water from the interior of the bed to the surface. For a pore formed by regularly packed nonporous spheres, the suction potential is given by

$$P_s = x\sigma/r\rho g \qquad (12\text{-}35)$$

where P_s = suction potential, m of water; σ = surface tension; dyn/m; ρ = density of water, kg/m³; g = 9.8 m/s²; r = sphere radius, m; and x is a packing factor equal to 12.9 for rhombohedral and 4.8 for cubical packing.

As drying proceeds, the surface moisture evaporates, causing retreat of the surface menisci until the suction potential reaches a value given by Eq. (12-35). At this point, the pores of the surface will open, air will enter, and the moisture will redistribute itself with a slight lowering of the suction potential. As evaporation proceeds, the suction potential again increases until a slightly higher entry value is reached, when a further redistribution occurs.

The drying rate curve (Fig. 12-41) can be analyzed in terms of capillary theory. In region *BC*, there is a loss of moisture with a gradual increase in suction and emptying of the bulk of the larger pores in the solid. In region *CE*, there is an increase in suction as the moisture content decreases and finer pores are opened. Section *ED* represents a condition in which moisture is being removed by vapor diffusion from the interior of the body, although there is still sufficient water in the bed to give rise to capillary forces.

An approximate equation for use for materials in which moisture movement is controlled by capillary flow is given as

$$\theta_f = \frac{\rho_s\, d\lambda (W_c - W_e)}{h_t(t - t'_s)} \ln \frac{W_c - W_e}{W - W_e} \qquad (12\text{-}36)$$

where θ_f = drying time in the falling-rate period.

Table 12-6 gives an approximate classification of materials that obey Eqs. (12-34) and (12-36).

CRITICAL MOISTURE CONTENT

To use the preceding equations for estimating drying times in the falling-rate period, it is necessary to know values of critical moisture content W_c. Such values are difficult to obtain without making actual drying tests, which in themselves would give the required drying time and thereby obviate solving the equations. However, when drying tests are not feasible, some estimate of critical moisture content must be made.

Values of critical moisture contents for some representative materials are given in Table 12-7 for drying by cross circulation and in Table 12-15 for drying by through circulation. The tabulated values are only approximate, since critical moisture content depends on the drying history. It appears that the constant-rate period ends when the moisture content at the surface reaches a specific value. Since the critical

TABLE 12-6 Materials Obeying Eqs. (12-34) and (12-38)

Materials obeying Eq. (12-34)	Materials obeying (Eq. 12-38)
1. Single-phase solid systems such as soap, gelatin, and glue 2. Wood and similar solids below the fiber-saturation point 3. Last stages of drying starches, textiles, paper, clay, hydrophilic solids, and other materials when bound water is being removed	1. Coarse granular solids such as sand, paint pigments, and minerals 2. Materials in which moisture flow occurs at concentrations above the equilibrium moisture content at atmospheric saturation or above the fiber-saturation point

TABLE 12-7 Approximate Critical Moisture Contents Obtained on the Air Drying of Various Materials, Expressed as Percentage Water on the Dry Basis

Material	Thickness, in.	Critical moisture, % water, dry basis
Barium nitrate crystals, on trays	1.0	7
Beaverboard	0.17	Above 120
Brick clay	.62	14
Carbon pigment	1	40
Celotex	0.44	160
Chrome leather	.04	125
Copper carbonate (on trays)	1–1.5	60
English china clay	1	16
Flint clay refractory brick mix	2.0	13
Gelatin, initially 400 % water	0.1–0.2 (wet)	300
Iron blue pigment (on trays)	0.25–0.75	110
Kaolin		14
Lithol red	1	50
Lithopone press cake (in trays)	0.25	6.4
	.50	8.0
	.75	12.0
	1.0	16.0
Niter cake fines, on trays		Above 16
Paper, white eggshell	0.0075	41
Fine book	.005	33
Coated	.004	34
Newsprint		60–70
Plastic clay brick mix	2.0	19
Poplar wood	0.165	120
Prussian blue		40
Pulp lead, initially 140% water		Below 15
Rock salt (in trays)	1.0	7
Sand, 50–150 mesh	2.0	5
Sand, 200–325 mesh	2.0	10
Sand, through 325 mesh	2.0	21
Sea sand (on trays)	0.25	3
	.5	4.7
	.75	5.5
	1.0	5.9
	2.0	6.0
Silica brick mix	2.0	8
Sole leather	0.25	Above 90
Stannic tetrachloride sludge	1	180
Subsoil, clay fraction 55.4%		21
Subsoil, much higher clay content		35
Sulfite pulp	0.25–0.75	60–80
Sulfite pulp (pulp lap)	0.039	110
White lead		11
Whiting	0.25–1.5	6.9
Wool fabric, worsted		31
Wool, undyed serge		8

moisture content is the average moisture through the material, its value depends on the rate of drying, the thickness of the material, and the factors influencing moisture movement and resulting gradients within the solid. As a result, the critical moisture content increases with increased drying rate and with increased thickness of the mass of material being dried.

EQUILIBRIUM MOISTURE CONTENT

In drying solids it is important to distinguish between hygroscopic and nonhygroscopic materials. If a hygroscopic material is maintained in contact with air at constant temperature and humidity until equilibrium is reached, the material will attain a definite moisture content. This moisture is termed the equilibrium moisture content for the specified conditions. Equilibrium moisture may be adsorbed as a surface film or condensed in the fine capillaries of the solid at reduced pressure, and its concentration will vary with the temperature and humidity of the surrounding air. However, at low temperatures, e.g., 15 to 50°C, a plot of equilibrium moisture content versus percent relative humidity is essentially independent of temperature. At zero humidity the equilibrium moisture content of all materials is zero.

Equilibrium moisture content depends greatly on the nature of the solid. For nonporous, i.e., nonhygroscopic, materials, the equilibrium moisture content is essentially zero at all temperatures and humidities. For organic materials such as wood, paper, and soap, equilibrium moisture contents vary regularly over wide ranges as temperature and humidity change. In the special case of the dehydration of hydrated inorganic salts such as copper sulfate, sodium sulfate, or barium chloride, temperature and humidity control is very important in obtaining the desired degree of moisture removal, and the proper conditions must be determined from data on the water of hydration or crystallization as a function of air temperature and humidity.

Equilibrium moisture content of a solid is particularly important in drying because it represents the limiting moisture content for given conditions of humidity and temperature. If the material is dried to a moisture content less than it normally possesses in equilibrium with atmospheric air, it will return to its equilibrium value on storage unless special precautions are taken.

Equilibrium moisture content of a hygroscopic material may be determined in a number of ways, the only requirement being a source of constant-temperature and constant-humidity air. Determination may be made under static or dynamic conditions, although the latter case is preferred. A simple static procedure is to place a number of samples in ordinary laboratory desiccators containing sulfuric acid solutions of known concentrations which produce atmospheres of known relative humidity. The sample in each desiccator is weighed periodically until a constant weight is obtained. Moisture content at this final weight represents the equilibrium moisture content for the particular conditions.

The value of equilibrium moisture content, for many materials, depends on the direction in which equilibrium is approached. A different value is reached when a wet material loses moisture by desorption, as in drying, from that obtained when a dry material gains it by adsorption. For drying calculations the desorption values are preferred. In the general case, the equilibrum moisture content reached by losing moisture is higher than that reached by adsorbing it.

Equilibrium moisture content can be measured dynamically by placing the sample in a U tube through which is drawn a continuous flow of controlled-humidity air. Again the sample is weighed periodically until a constant weight is reached. Properly humidified air for such a procedure can be obtained by bubbling dry air through a large volume of a saturated salt solution which produces a definite degree of saturation of the air. Care must be taken to ensure that the air and salt solution reach equilibrium. Values of the humidity over various salt solutions may be found in Table 12-8. Several manufacturers supply chambers with dial-in temperature and humidity conditions for air-water systems.

ESTIMATIONS FOR TOTAL DRYING TIME

Estimates of both the constant-rate and the falling-rate periods are needed to estimate the total drying time for a given drying operation. If estimates for these periods are available, the total drying time is estimated by summing as

$$\theta_t = \theta_c + \theta_f \tag{12-37}$$

where θ_t = total drying time, h; θ_c = drying time for constant-rate period, h; and θ_f = drying time for falling-rate period, h. The difficulty in estimating critical moisture content greatly reduces the number of drying cases in which calculation of a good estimate is possible.

ANALYSIS OF DRYING DATA TESTS ON PLANT DRYERS

When experiments are carried out to select a suitable dryer and to obtain design data, the effect of changes in various external variables is studied. These experiments should be conducted in an experimental unit that simulates the large-scale dryer from both the thermal and the material-handling aspects, and only material which is truly representative of full-scale production should be used.

Data expressing moisture content in terms of elapsed time should be obtained and the results plotted as shown in Fig. 12-42. For purposes of analysis, the moisture-time curve must be differentiated

TABLE 12-8 Maintenance of Constant Humidity

Solid phase	Max. temp., °C.	% humidity
$H_3PO_4\cdot\frac{1}{2}H_2O$	24.5	9
$ZnCl_2\cdot\frac{1}{2}H_2O$	20	10
$KC_2H_3O_2$	168	13
$LiCl\cdot H_2O$	20	15
$KC_2H_3O_2$	20	20
KF	100	22.9
NaBr	100	22.9
$CaCl_2\cdot 6H_2O$	24.5	31
$CaCl_2\cdot 6H_2O$	20	32.3
$CaCl_2\cdot 6H_2O$	18.5	35
CrO_3	20	35
$CaCl_2\cdot 6H_2O$	10	38
$CaCl_2\cdot 6H_2O$	5	39.8
$K_2CO_3\cdot 2H_2O$	24.5	43
$K_2CO_3\cdot 2H_2O$	18.5	44
$Ca(NO_3)_2\cdot 4H_2O$	24.5	51
$NaHSO_4\cdot H_2O$	20	52
$Mg(NO_3)_2\cdot 6H_2O$	24.5	52
$NaClO_3$	100	54
$Ca(NO_3)_2\cdot 4H_2O$	18.5	56
$Mg(NO_3)_2\cdot 6H_2O$	18.5	56
$NaBr\cdot 2H_2O$	20	58
$Mg(C_2H_3O_2)\cdot 4H_2O$	20	65
$NaNO_2$	20	66
$(NH_4)_2SO_4$	108.2	75
$(NH_4)_2SO_4$	20	81
$NaC_2H_3O_2\cdot 3H_2O$	20	76
$Na_2S_2O_3\cdot 5H_2O$	20	78
NH_4Cl	20	79.5
NH_4Cl	25	79.3
NH_4Cl	30	77.5
KBr	20	84
Tl_2SO_4	104.7	84.8
$KHSO_4$	20	86
$Na_2CO_3\cdot 10H_2O$	24.5	87
K_2CrO_4	20	88
$NaBrO_3$	20	92
$Na_2CO_3\cdot 10H_2O$	18.5	92
$Na_2SO_4\cdot 10H_2O$	20	93
$Na_2HPO_4\cdot 12H_2O$	20	95
NaF	100	96.6
$Pb(NO_3)_2$	20	98
$TlNO_3$	100.3	98.7
TlCl	100.1	99.7

For a more complete list of salts, and for references to the literature see "International Critical Tables," vol. 1, p. 68.

graphically or numerically and the drying rates so obtained plotted to determine the nature and extent of the drying periods in the cycle. It is customary to plot drying rate versus moisture content as in Fig. 12-41*b*. Although instructive, this type of plot gives no information on duration of the drying periods. These are better shown by plots similar to Fig. 12-41*c*, in which drying rate is plotted as a function of time on either arithmetic or logarithmic coordinates. Logarithmic plots permit easy reading at low moisture contents or long times.

In order to determine whether a simple relationship exists in the falling-rate period, the unaccomplished moisture change, defined as ratio of free moisture in the solid at time θ to total free moisture present at start of the falling-rate period $(W - W_e)/(W_c - W_e)$, is plotted as a function of time on semilogarithmic paper. If a straight line is obtained such as curve *B* of Fig. 12-43 by using the upper scale of abscissa, either Eq. (12-34), for materials in which the moisture moves by diffusion, or Eq. (12-37), for materials in which the moisture movement is by capillary flow, may be applicable. If Eq. (12-37) applies, K_1, the slope of the falling-rate drying curve, is related to the constant drying rate. The latter is calculated from Eq. (12-38) and can be compared with the measured value. If the slopes agree, the moisture movement is by capillary flow. If the slopes do not agree, the moisture movement is by diffusion and the slope of the line should equal $\pi^2 D_\ell/4d^2$.

The dependency of drying rate on material thickness must be established experimentally. With the effect of material thickness established, liquid diffusivity can be calculated as indicated here. For this calculation, the theoretical values for an infinite slab are required. These are:

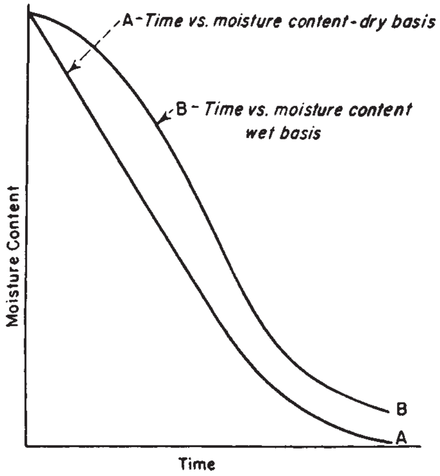


FIG. 12-42 Drying-time curves.

$\dfrac{D_\ell\theta}{d^2}$	0.02	0.05	0.10	0.15	0.20	0.30	0.50	1.0
$\dfrac{W - W_e}{W_c - W_e}$	0.84	0.75	0.642	0.563	0.496	0.387	0.238	0.069

A plot of these values is shown as curve *A* in Fig. 12-43.

If a straight line such as curve *B* of Fig. 12-43 represents the experimental data and if it has been established that the drying time varies inversely as the square of the thickness, the average liquid diffusivity can be obtained as follows. At a given value of $(W - W_e)/(W_c - W_e)$, read the corresponding value of $D_\ell\theta/d^2$ from curve *A*, Eq. (12-32), Fig. 12-43. At the same value of $(W - W_e)/(W_c - W_e)$, read the corresponding experimental value of θ from curve *B* (upper scale). Then

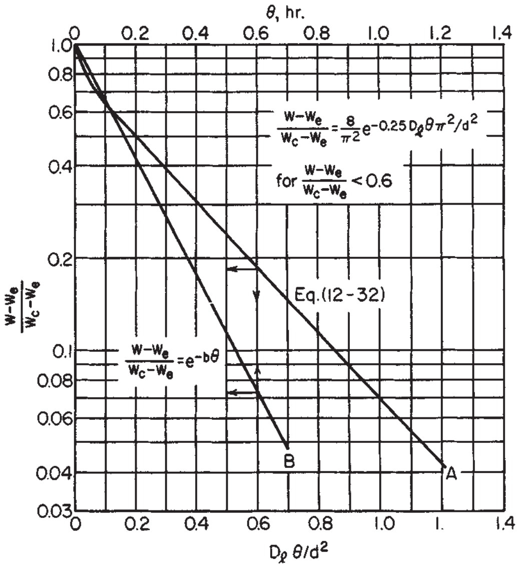


FIG. 12-43 Analysis of drying data.

$$D_{\ell_{\text{avg}}} = \frac{(D_\ell \theta/d^2)\ \text{theoretical}}{(\theta/d^2)\ \text{experimental}} \tag{12-38}$$

where $D_{\ell_{\text{avg}}}$ = average experimental value of liquid diffusivity, m²/h.

The value of diffusivity calculated from Eq. (12-38) must be recognized as an average value over the entire range of moisture change from $(W - W_e)/(W_c - W_e) = 1$ to the value $(W - W_c)/(W_c - W_e)$ at which θ/d^2 was evaluated. Further, Eq. (12-38) assumes that the theoretical curve is a straight line for all values of time. This is not true for values $(W - W_e)/(W_c - W_e)$ less than 0.6.

A more accurate value of $D_{\ell_{\text{avg}}}$ can be obtained by taking a ratio of slopes of the curves of Fig. 12-43. Thus the ratio of the slope of the experimental curve of unaccomplished moisture change versus drying time on a semilogarithmic plot [Eq. (12-32)] to the slope of the theoretical curve at the same unaccomplished moisture change, again on a semilogaritmic plot, equals the quantity D_ℓ/d^2. If d is known, D_ℓ can be evaluated.

TESTS ON PLANT DRYERS

Tests on plant-scale dryers are usually carried out to obtain design data for a specific material, to select a suitable dryer type, or to check present performance of an existing dryer with the objective of determining its capacity potential. In these tests overall performance data are obtained and the results used to make heat and material balances and to estimate overall drying rates or heat-transfer coefficients.

Generally, the minimum data to be taken in order to calculate the performance of a dryer are:

1. Inlet and outlet moisture contents
2. Inlet and outlet gas temperatures
3. Inlet and outlet material temperatures
4. Feed rate
5. Gas rate
6. Inlet and outlet humidities
7. Retention time or time of passage through the dryer
8. Fuel consumption

Whenever possible, moisture contents and temperatures should be measured at various points within the dryer.

Typical experimental and calculated results of a drying test for a continuous adiabatic convection dryer are shown in Fig. 12-44. Test data as elaborate as those shown are not usually justified economically except when basic studies, aimed at clarifying the effect of operating variables, are being carried out in order to arrive at a reliable design procedure. The completeness of the information which is sought in any given test depends on the ultimate use of the data. In any case data for at least two sets of operating conditions are needed if a good analysis of dryer performance is to be made.

Results of drying tests can be correlated empirically in terms of **overall heat-transfer coefficient** or **length of a transfer unit** as a function of operating variables. The former is generally applicable to all types of dryers, while the latter applies only in the case of continuous dryers. The relationship between these quantities is as follows.

The number of transfer units in any direct dryer is given by

$$N_t = (t_1 - t_2)/\Delta t_m \tag{12-39}$$

where N_t = number of transfer units; t_1 = inlet gas temperature, K; t_2 = exit gas temperature; and Δt_m = mean temperature difference between gas and solids through the dryer, K.

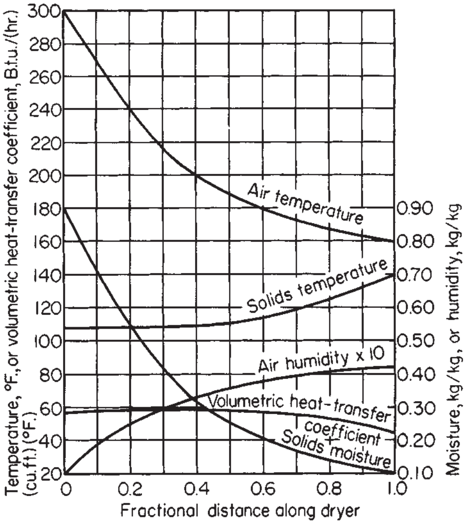


FIG. 12-44 Typical results of dryer-performance tests. To convert British thermal units per hour-cubic foot-degree Fahrenheit to joules per cubic meter-second-kelvin, multiply by 1.73.

The volumetric heat-transfer coefficient is given by

$$U_v = \frac{q_\text{d}}{V_d\,\Delta t_m} = \frac{wc_s(t_2 - t_1)}{A_d L_d\,\Delta t_m} \tag{12-40}$$

where U_v = volumetric heat-transfer coefficient, J/(m³·s·K) [Btu/(h·ft³·°F)]; q = cross-sectional area of dryer, m²; and L_d = dryer length, m.

The volumetric heat-transfer coefficients along the dryer are lower at the discharge end (Fig. 12-44) because of the internal resistance to moisture movement in the later stages of drying. When drying data are expressed in terms of overall performance, care and judgment should be exercised in extrapolating the results to other conditions, particularly conditions of different feed and product moisture. If, for example, the overall heat-transfer coefficients, from the data of Fig. 12-44, were used to predict a dryer design for reducing the product moisture below 10 percent, the design would be in error. Obviously, this problem can be circumvented by making sure that the final moisture in the experiments is below that desired in the product.

In any capacity test to determine the potential of a plant dryer, the effects of the following variables should be studied:

1. **Effect of increased temperature.** This is often the simplest way to achieve increased capacity.
2. **Effect of increased final moisture.** Because of the marked increase in drying time required to dry to low moisture contents, the permissible maximum final moisture should always be established.
3. **Effect of increasing air velocity** should be determined. Frequently, higher air rates are necessary to provide the required additional heat at higher capacities.
4. **Uniformity of air flow** should be established. Air-flow maldistribution can seriously reduce dryer capacity and efficiency.
5. Possible benefits from **air recirculation** should be considered.

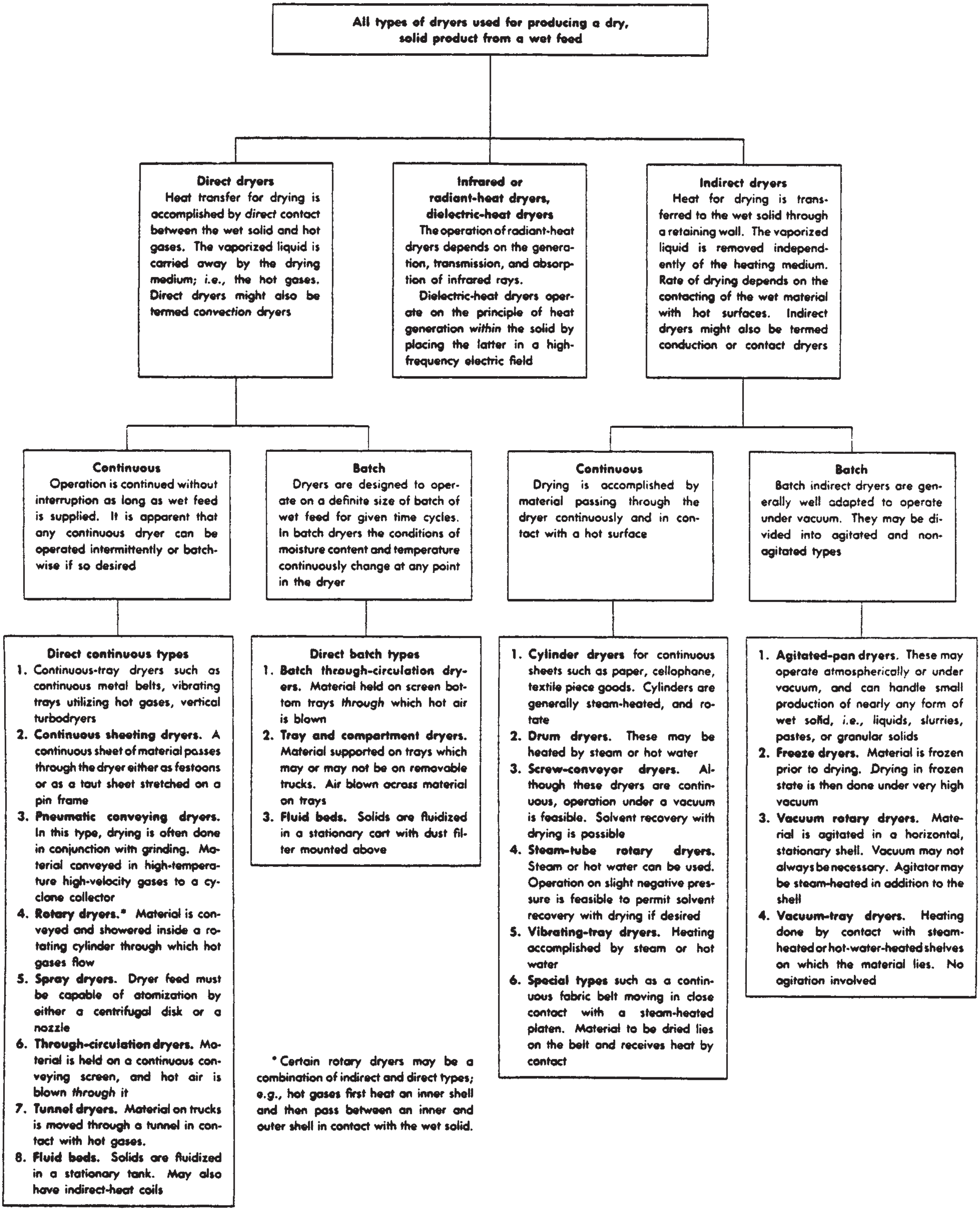
SOLIDS-DRYING EQUIPMENT

CLASSIFICATION OF DRYERS

Drying equipment may be classified in several ways. The two most useful classifications are based on (1) the method of transferring heat to the wet solids or (2) the handling characteristics and physical properties of the wet material. The first method of classification reveals differences in dryer design and operation, while the second method is most useful in the selection of a group of dryers for preliminary consideration in a given drying problem.

A classification chart of drying equipment on the basis of heat transfer is shown in Fig. 12-45. This chart classifies dryers as direct or indirect, with subclasses of continuous or batchwise operation.

Direct Dryers The general operating characteristics of direct dryers are these:



All types of dryers used for producing a dry, solid product from a wet feed

Direct dryers
Heat transfer for drying is accomplished by *direct* contact between the wet solid and hot gases. The vaporized liquid is carried away by the drying medium; *i.e.*, the hot gases. Direct dryers might also be termed *convection* dryers

Infrared or radiant-heat dryers, dielectric-heat dryers
The operation of radiant-heat dryers depends on the generation, transmission, and absorption of infrared rays.

Dielectric-heat dryers operate on the principle of heat generation *within* the solid by placing the latter in a high-frequency electric field

Indirect dryers
Heat for drying is transferred to the wet solid through a retaining wall. The vaporized liquid is removed independently of the heating medium. Rate of drying depends on the contacting of the wet material with hot surfaces. Indirect dryers might also be termed conduction or contact dryers

Continuous
Operation is continued without interruption as long as wet feed is supplied. It is apparent that any continuous dryer can be operated intermittently or batchwise if so desired

Batch
Dryers are designed to operate on a definite size of batch of wet feed for given time cycles. In batch dryers the conditions of moisture content and temperature continuously change at any point in the dryer

Continuous
Drying is accomplished by material passing through the dryer continuously and in contact with a hot surface

Batch
Batch indirect dryers are generally well adapted to operate under vacuum. They may be divided into agitated and nonagitated types

Direct continuous types

1. Continuous-tray dryers such as continuous metal belts, vibrating trays utilizing hot gases, vertical turbodryers
2. **Continuous sheeting dryers.** A continuous sheet of material passes through the dryer either as festoons or as a taut sheet stretched on a pin frame
3. **Pneumatic conveying dryers.** In this type, drying is often done in conjunction with grinding. Material conveyed in high-temperature high-velocity gases to a cyclone collector
4. **Rotary dryers.*** Material is conveyed and showered inside a rotating cylinder through which hot gases flow
5. **Spray dryers.** Dryer feed must be capable of atomization by either a centrifugal disk or a nozzle
6. **Through-circulation dryers.** Material is held on a continuous conveying screen, and hot air is blown *through* it
7. **Tunnel dryers.** Material on trucks is moved through a tunnel in contact with hot gases.
8. **Fluid beds.** Solids are fluidized in a stationary tank. May also have indirect-heat coils

Direct batch types

1. **Batch through-circulation dryers.** Material held on screen bottom trays *through* which hot air is blown
2. **Tray and compartment dryers.** Material supported on trays which may or may not be on removable trucks. Air blown *across* material on trays
3. **Fluid beds.** Solids are fluidized in a stationary cart with dust filter mounted above

1. **Cylinder dryers** for continuous sheets such as paper, cellophane, textile piece goods. Cylinders are generally steam-heated, and rotate
2. **Drum dryers.** These may be heated by steam or hot water
3. **Screw-conveyor dryers.** Although these dryers are continuous, operation under a vacuum is feasible. Solvent recovery with drying is possible
4. **Steam-tube rotary dryers.** Steam or hot water can be used. Operation on slight negative pressure is feasible to permit solvent recovery with drying if desired
5. **Vibrating-tray dryers.** Heating accomplished by steam or hot water
6. **Special types** such as a continuous fabric belt moving in close contact with a steam-heated platen. Material to be dried lies on the belt and receives heat by contact

1. **Agitated-pan dryers.** These may operate atmospherically or under vacuum, and can handle small production of nearly any form of wet solid, *i.e.*, liquids, slurries, pastes, or granular solids
2. **Freeze dryers.** Material is frozen prior to drying. Drying in frozen state is then done under very high vacuum
3. **Vacuum rotary dryers.** Material is agitated in a horizontal, stationary shell. Vacuum may not always be necessary. Agitator may be steam-heated in addition to the shell
4. **Vacuum-tray dryers.** Heating done by contact with steam-heated or hot-water-heated shelves on which the material lies. No agitation involved

*Certain rotary dryers may be a combination of indirect and direct types; e.g., hot gases first heat an inner shell and then pass between an inner and outer shell in contact with the wet solid.

FIG. 12-45 Classification of dryers, based on method of heat transfer. [*Revised from Marshall,* Heat, Piping Air Cond., ***18,*** *71 (1946).*]

1. Direct contacting of hot gases with the solids is employed for solids heating and vapor removal.
2. Drying temperatures may range up to 1000 K, the limiting temperature for most common structural metals. At the higher temperatures, radiation becomes an important heat-transfer mechanism.
3. At gas temperatures below the boiling point, the vapor content of gas influences the rate of drying and the final moisture content of the solid. With gas temperatures above the boiling point throughout, the vapor content of the gas has only a slight retarding effect on the drying rate and final moisture content. Thus, superheated vapors of the liquid being removed can be used for drying.
4. For low-temperature drying, dehumidification of the drying air may be required when atmospheric humidities are excessively high.
5. A direct dryer consumes more fuel per pound of water evaporated, the lower the final moisture content.
6. Efficiency increases with an increase in the inlet-gas temperature for a constant exhaust temperature.
7. Because large amounts of gas are required to supply all the heat for drying, dust-recovery equipment may be very large and expensive when drying very small particles.

Indirect Dryers These differ from direct dryers with respect to heat transfer and vapor removal:

1. Heat is transferred to the wet material by conduction through a solid retaining wall, usually metallic.
2. Surface temperatures may range from below freezing in the case of freeze dryers to above 800 K in the case of indirect dryers heated by combustion products.
3. Indirect dryers are suited to drying under reduced pressures and inert atmospheres to permit the recovery of solvents and to prevent the occurrence of explosive mixtures or the oxidation of easily decomposed materials.
4. Indirect dryers using condensing fluids as the heating medium are generally economical from the standpoint of heat consumption, since they furnish heat only in accordance with the demand made by the material being dried.
5. Dust recovery and dusty materials can be handled more satisfactorily in indirect dryers than in direct dryers.

Miscellaneous Dryers **Infrared dryers** depend on the transfer of radiant energy to evaporate moisture. The radiant energy is supplied electrically by infrared lamps, by electric resistance elements, or by incandescent refractories heated by gas. The latter method has the added advantage of convection heating. Infrared heating is not widely used in the chemical industries for the removal of moisture. Its principal use is in baking or drying paint films and in heating thin layers of materials.

Dielectric dryers have not as yet found a wide field of application. Their fundamental characteristic of generating heat within the solid indicates potentialities for drying massive geometrical objects such as wood, sponge-rubber shapes, and ceramics. Power costs may range to 10 times the fuel costs of conventional methods.

SELECTION OF DRYING EQUIPMENT

1. *Initial selection of dryers.* Select those dryers which appear best suited to handling the wet material and the dry product, which fit into the continuity of the process as a whole, and which will produce a product of the desired physical properties. This preliminary selection can be made with the aid of Table 12-9, which classifies the various types of dryers on the basis of the materials handled.
2. *Initial comparison of dryers.* The dryers so selected should be evaluated approximately from available cost and performance data. From this evaluation, those dryers which appear to be uneconomical or unsuitable from the standpoint of performance should be eliminated from further consideration.
3. *Drying tests.* Drying tests should be conducted in those dryers still under consideration. These tests will determine the optimum operating conditions and the product characteristics and will form the basis for firm quotations from equipment vendors.
4. *Final selection of dryer.* From the results of the drying tests and quotations, the final selection of the most suitable dryer can be made. A recent article describing dryer scale-up methodology in the process industries was recently published by L. R. Genskow [*Drying Technology—An International Journal,* **12**(1&2), 47 (1994)].

The important factors to consider in the preliminary selection of a dryer are the following:

1. Properties of the material being handled
    - *a.* Physical characteristics when wet
    - *b.* Physical characteristics when dry
    - *c.* Corrosiveness
    - *d.* Toxicity
    - *e.* Flammability
    - *f.* Particle size
    - *g.* Abrasiveness
2. Drying characteristics of the material
    - *a.* Type of moisture (bound, unbound, or both)
    - *b.* Initial moisture content
    - *c.* Final moisture content (maximum)
    - *d.* Permissible drying temperature
    - *e.* Probable drying time for different dryers
3. Flow of material to and from the dryer
    - *a.* Quantity to be handled per hour
    - *b.* Continuous or batch operation
    - *c.* Process prior to drying
    - *d.* Process subsequent to drying
4. Product qualities
    - *a.* Shrinkage
    - *b.* Contamination
    - *c.* Uniformity of final moisture content
    - *d.* Decomposition of product
    - *e.* Overdrying
    - *f.* State of subdivision
    - *g.* Product temperature
    - *h.* Bulk density
5. Recovery problems
    - *a.* Dust recovery
    - *b.* Solvent recovery
6. Facilities available at site of proposed installation
    - *a.* Space
    - *b.* Temperature, humidity, and cleanliness of air
    - *c.* Available fuels
    - *d.* Available electric power
    - *e.* Permissible noise, vibration, dust, or heat losses
    - *f.* Source of wet feed
    - *g.* Exhaust-gas outlets

The physical nature of the material to be handled is the primary item for consideration. A slurry will demand a different type of dryer from that required by a coarse crystalline solid, which, in turn, will be different from that required by a sheet material (Table 12-9).

Following preliminary selection of suitable types of dryers, a high-spot evaluation of the size and cost should be made to eliminate those which are obviously uneconomical. Information for this evaluation can be obtained from material presented under discussion of the various dryer types. When data are inadequate, preliminary cost and performance data can usually be obtained from the equipment manufacturer. In comparing dryer performance, the factors in the preceding list which affect dryer performance should be properly weighed. The possibility of eliminating or simplifying processing steps which precede or follow drying, such as filtration, grinding, or conveying, should be carefully considered.

DRYING TESTS

These tests should establish the optimum operating conditions, the ability of the dryer to handle the material physically, product quality and characteristics, and dryer size. The principal manufacturers of drying equipment are usually prepared to perform the required tests on dryers simulating their equipment. Occasionally, simple laboratory experiments can serve to reduce further the number of dryers under consideration.

Once a given type and size of dryer has been installed, the product characteristics and drying capacity can be changed only within relatively narrow limits. Thus it is more economical and far more satisfac-

TABLE 12-9 Classification of Commercial Dryers Based on Materials Handled

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline, or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions; emulsions. Examples: inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex, etc.	Pumpable suspensions. Examples: pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates, etc.	Examples: filter-press cakes, sedimentation sludges, centrifuged solids, starch, etc.	100 mesh or less. Relatively free flowing in wet state. Dusty when dry. Examples: centrifuged precipitates, pigments, clay, cement.	Larger than 100 mesh. Examples: rayon staple, salt crystals, sand, ores, potato strips, synthetic rubber.	Examples: pottery, brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber.	Examples: paper, impregnated fabrics, cloth, cellophane, plastic sheets.	Examples: veneer, wallboard, photograph prints, leather, foam rubber sheets.
Vacuum freeze. Indirect type, batch or continuous operation	Usually used only for pharmaceuticals such as penicillin and blood plasma. Expensive. Used on heat-sensitive and readily oxidized materials	See comments under Liquids	See comments under Liquids	See comments under Liquids	Expensive. Usually used on pharmaceuticals and related products which cannot be dried successfully by other means. Applicable to fine chemicals	See comments under Granular solids	Applicable in special cases such as emulsion-coated films	See comments under Granular solids
Pan. Indirect type, batch operation	Atmospheric or vacuum. Suitable for small batches. Easily cleaned. Solvents can be recovered. Material agitated while dried	See comments under Liquids	See comments under Liquids	See comments under Liquids	Suitable for small batches. Easily cleaned. Material is agitated during drying, causing some degradation	Not applicable	Not applicable	Not applicable
Vacuum rotary. Indirect type, batch operation	Not applicable, except when pumping slowly on dry "heel"	May have application in special cases when pumping onto dry "heel"	Use is questionable. Material usually cakes to dryer walls and agitator. Solvents can be recovered	Suitable for nonsticking materials. Useful for large batches of heat-sensitive materials and for solvent recovery	Useful for large batches of heat-sensitive materials or where solvent is to be recovered. Product will suffer some grinding action. Dust collectors may be required.	Not applicable	Not applicable	Not applicable
Screw conveyor and indirect rotary. Indirect type, continuous operation	Applicable with dry-product recirculation	Applicable with dry-product recirculation	Generally requires recirculation of dry product. Little dusting occurs	Chief advantage is low dust loss. Well suited to most materials and capacities, particularly those requiring drying at steam temperature	Low dust loss. Material must not stick or be temperature-sensitive	Not applicable	Not applicable	Not applicable
Fluid beds. Batch, continuous, direct, and indirect	Applicable only with inert bed or dry-solids recirculator	See comments under Liquids	See comments under Liquids	Suitable, if not too dusty	Suitable for crystals, granules, and short fibers	Not applicable	Use hot inert particles for contacting	Use hot inert particles for contacting
Vibrating tray. Indirect type, continuous operation	Not applicable	Not applicable	Not applicable	Suitable for free-flowing materials	Suitable for free-flowing materials that can be conveyed on a vibrating tray	Not applicable	Not applicable	Not applicable

TABLE 12-9 Classification of Commercial Dryers Based on Materials Handled (*Concluded*)

	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline, or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
Drum. Indirect type, continuous operation	Single, double or twin. Atm. or vacuum operation. Product flaky and usually dusty. Maintenance costs may be high	See comments under Liquids. Twin-drum dryers are widely used	Can be used only when paste or sludge can be made to flow. See comments under Liquids	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Cylinder. Indirect type, continuous operation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Suitable for thin or mechanically weak sheets which can be dried in contact with a heated surface. Special surface effects obtainable	Suitable for materials which need not be dried flat and which will not be injured by contact with hot drum
Infrared. Batch or continuous operation	Only for thin films	See comments under Liquids	See comments under Liquids (only for thin layers)	Only for thin layers	Primarily suited to drying surface moisture. Not suited for thick layers	Specially suited for drying and baking paint and enamels	Usually used in conjunction with other methods. Useful when there are space limitations	Useful for laboratory work or in conjunction with other methods
Dielectric. Batch or continuous operation	Very expensive	See comments under Liquids	See comments under Liquids	Very expensive	Very expensive	Rapid drying of large objects suited to this method	Applications for final stages of paper dryers	Successful on foam rubber. Not fully developed on other materials
Tray and compartment. Direct type, batch operation	Not applicable	For very small batch production. Laboratory drying	Suited to batch operation. At large capacities, investment and operating costs are high. Long drying times	Dusting may be a problem. See comments under Pastes and Sludges	Suited to batch operation. At large capacities, investment and operating costs are high. Long drying times	See comments under Granular solids	Not applicable	See comments under Granular solids
Batch through-circulation. Direct type, batch operation	Not applicable	Not applicable	Suitable only if material can be preformed. Suited to batch operation. Shorter drying time than tray dryers	Not applicable	Usually not suited for materials smaller than 30 mesh. Suited to small capacities and batch operation	Primarily useful for small objects	Not applicable	Not applicable
Tunnel. Continuous Tray. Direct type, continuous operation	Not applicable	Not applicable	Suitable for small and large-scale production.	See comments under Pastes and Sludges. Vertical-turbo applicable	Essentially large-scale, semicontinuous tray drying.	Suited to a wide variety of shapes and forms. Operation can be made continuous. Widely used	Not applicable	Suited for leather, wallboard, veneer.
Continuous through-circulation. Direct type, continuous operation	Not applicable	Only crystal filter dryer may be suited	Suitable for materials that can be preformed. Will handle large capacities. Roto-louvre requires dry-product recirculation	Not generally applicable, except Roto-louvre in certain cases	Usually not suited for materials smaller than 30 mesh. Material does not tumble, except in Roto-louvre dryer. Latter operates at higher temperatures	Suited to smaller objects that can be loaded on each other. Can be used to convey materials through heated zones. Roto-louvre not suited.	Not applicable	Special designs are required. Suited to veneers. Roto-louvre not applicable
Direct rotary. Direct type, continuous operation		Applicable with dry-product recirculation	Suitable only if product does not stick to walls and	Suitable for most materials and capacities, pro-	Suitable for most materials at most capacities. Dust-	Not applicable	Not applicable	Not applicable

TABLE 12-9 Classification of Commercial Dryers Based on Materials Handled (*Concluded*)

	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline, or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	Applicable with dry-product recirculation		does not dust. Recirculation of product may prevent sticking	vided that dusting is not too severe	ing or crystal abrasion will limit its use			
Type of dryer	True and colloidal solutions; emulsions. Examples: inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex, etc.	Pumpable suspensions. Examples: pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates, etc.	Examples: filter-press cakes, sedimentation sludges, centrifuged solids, starch, etc.	100 mesh or less. Relatively free flowing in wet state. Dusty when dry. Examples: centrifuged precipitates, pigments, clay, cement.	Larger than 100 mesh. Examples: rayon staple, salt crystals, sand, ores, potato strips, synthetic rubber.	Examples: pottery, brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber.	Examples: paper, impregnated fabrics, cloth, cellophane, plastic sheets.	Examples: veneer, wallboard, photograph prints, leather, foam rubber sheets.
Pneumatic conveying. Direct type, continuous operation	See comments under Slurries	Can be used only if product is recirculated to make feed suitable for handling	Usually requires recirculation of dry product to make suitable feed. Well suited to high capacities. Disintegration usually required	Suitable for materials that are easily suspended in a gas stream and lose moisture readily. Well suited to high capacities	Suitable for materials that are easily suspended in a gas streatm. Well suited to high capacities. Product may suffer physical degradation	Not applicable	Not applicable	Not applicable
Spray. Direct type, continuous operation	Suited for large capacities. Product is usually powdery, spherical, and free-flowing. High temperatures can be used with heat-sensitive materials. Product may have low bulk density	See comments under Liquids. Pressure-nozzle atomizers subject to erosion	Requires special pumping equipment to feed the atomizer. See comments under Liquids	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Continuous sheeting. Direct type, continuous operation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Different types are available for different requirements. Suitable for drying without contacting hot surfaces	Not applicable
Vacuum shelf. Indirect type, batch operation	Not applicable	Applicable for small-batch production	Suitable for batch operation, small capacities. Useful for heat-sensitive or readily oxidizable materials. Solvents can be recovered	See comments under Pastes and Sludges	Suitable for batch operation, small capacities. Useful for heat-sensitive or readily oxidizable materials. Solvents can be recovered.	See comments under Granular solids	Not applicable	See comments under Granular solids

tory to experiment in small-scale units than on the dryer that is finally installed.

On the basis of the results of the drying tests that establish size and operating characteristics, formal quotations and guarantees should be obtained from dryer manufacturers. Initial costs, installation costs, operating costs, product quality, dryer operability, and dryer flexibility can then be given proper weight in final evaluation and selection.

BATCH TRAY AND DRYERS

Description A tray or compartment dryer is an enclosed, insulated housing in which solids are placed upon tiers of trays in the case of particulate solids or stacked in piles or upon shelves in the case of large objects. Heat transfer may be *direct* from gas to solids by circulation of large volumes of hot gas or *indirect* by use of heated shelves, radiator coils, or refractory walls inside the housing. In indirect-heat units, excepting vacuum-shelf equipment, circulation of a small quantity of gas is usually necessary to sweep moisture vapor from the compartment and prevent gas saturation and condensation. Compartment units are employed for the heating and drying of lumber, ceramics, sheet materials (supported on poles), painted and metal objects, and all forms of particulate solids.

Field of Application Because of the high labor requirements usually associated with loading or unloading the compartments, batch compartment equipment is rarely economical except in the following situations:

1. A long heating cycle is necessary because the size of the solid objects or permissible heating temperature requires a long holdup for internal diffusion of heat or moisture. This case may apply when the cycle will exceed 12 to 24 h.
2. The production of several different products requires strict batch identity and thorough cleaning of equipment between batches. This is a situation existing in many small color-pigment-drying plants.
3. The quantity of material to be processed does not justify investment in more expensive, continuous equipment. This case would apply in many pharmaceutical-drying operations.

Further, because of the nature of solids-gas contacting, which is usually by parallel flow and rarely by through circulation, heat transfer and mass transfer are comparatively inefficient. For this reason, use of tray and compartment equipment is restricted primarily to ordinary drying and heat-treating operations. Despite these harsh limitations, when the listed situations do exist, economical alternatives are difficult to develop.

Auxiliary Equipment If noxious gases, fumes, or dust are given off during the operation, dust- or fume-recovery equipment will be necessary in the exhaust-gas system. Wet scrubbers are employed for the recovery of valuable solvents from dryers. In order to minimize heat losses, thorough insulation of the compartment with brick, asbestos, or other insulating compounds is necessary. Modern fabricated dryer-compartment panels usually have 7.5 to 15 cm of blanket insulation placed between the internal and external sheet-metal walls. Doors and other access openings should be gasketed and tight. In the case of tray and truck equipment, it is usually desirable to have available extra trays and trucks so that they can be preloaded for rapid emptying and loading of the compartment between cycles. Air filters and gas dryers are occasionally employed on the inlet-air system for direct-heat units.

Vacuum-shelf dryers require auxiliary stream jets or other vacuum-producing devices, intercondensers for vapor removal, and occasionally wet scrubbers or (heated) bag-type dust collectors.

Uniform depth of loading in dryers and furnaces handling particulate solids is essential to consistent operation, minimum heating cycles, or control of final moisture. After a tray has been loaded, the bed should be leveled to a uniform depth. Special preform devices, noodle extruders, pelletizers, etc., are employed occasionally for preparing pastes and filter cakes so that screen bottom trays can be used and the advantages of through circulation approached.

Control of tray and compartment equipment is usually maintained by control of the circulating-air temperature (and humidity) and rarely by solids temperature. On vacuum units, control of the absolute pressure and heating-medium temperature is utilized. In direct dryers, cycle controllers are frequently employed to vary the air temperature or velocity across the solids during the cycle, e.g., high air temperatures may be employed during a constant-rate drying period while the solids surface remains close to the air wet-bulb temperature. During the falling-rate periods, this temperature may be reduced to prevent casehardening or other degrading effects caused by overheating the solids surfaces. In addition, higher air velocities may be employed during early drying stages to improve heat transfer; however, after surface drying has been completed, this velocity may need to be reduced to prevent dusting. Two-speed circulating fans are employed commonly for this purpose.

Direct-Heat Tray Dryers Satisfactory operation of tray-type dryers depends on maintaining a constant temperature and a uniform air velocity over all the material being dried.

Circulation of air at velocities of 1 to 10 m/s is desirable to improve the surface heat-transfer coefficient and to eliminate stagnant air pockets. Proper air flow in tray dryers depends on sufficient fan capacity, on the design of ductwork to modify sudden changes in direction, and on properly placed baffles. *Nonuniform air flow is one of the most serious problems in the operation of tray dryers.*

Tray dryers may be of the tray-truck or the stationary-tray type. In the former, the trays are loaded on trucks which are pushed into the dryer; in the latter, the trays are loaded directly into stationary racks within the dryer. Trucks may be fitted with flanged wheels to run on tracks or with flat swivel wheels. They may also be suspended from and moved on monorails. Trucks usually contain two tiers of trays, with 18 to 48 trays per tier, depending upon the tray dimensions.

Trays may be square or rectangular, with 0.5 to 1 m^2 per tray, and may be fabricated from any material compatible with corrosion and temperature conditions. When the trays are stacked in the truck, there should be a clearance of not less than 4 cm between the material in one tray and the bottom of the tray immediately above. When material characteristics and handling permit, the trays should have screen bottoms for additional drying area. Metal trays are preferable to nonmetallic trays, since they conduct heat more readily. Tray loadings range usually from 1 to 10 cm deep.

Steam is the usual heating medium, and a standard heater arrangement consists of a main heater before the circulating fan. When steam is not available or the drying load is small, electrical heat can be used. For temperatures above 450 K, products of combustion can be used, or indirect-fired air heaters.

Air is circulated by propeller or centrifugal fans; the fan is usually mounted within or directly above the dryer. Above 450 K, external or water-cooled bearings become necessary. Total pressure drop through the trays, heaters, and ductwork is usually in the range of 2.5 to 5 cm of water. Air recirculation is generally in the order of 80 to 95 percent except during the initial drying stage of rapid evaporation. Fresh air is drawn in by the circulating fan, frequently through dust filters. In most installations, air is exhausted by a separate small exhaust fan with a damper to control air-recirculation rates.

Prediction of Heat- and Mass-Transfer Coefficients in Direct-Heat Tray Dryers In convection phenomena, heat-transfer coefficients depend on the geometry of the system, the gas velocity past the evaporating surface, and the physical properties of the drying gas. In estimating drying rates, the use of heat-transfer coefficients is preferred because they are usually more reliable than mass-transfer coefficients. In calculating mass-transfer coefficients from drying experiments; the partial pressure at the surface is usually inferred from the measured or calculated temperature of the evaporating surface. Small errors in temperature have negligible effect on the heat-transfer coefficient but introduce relatively large errors in the partial pressure and hence in the mass-transfer coefficient.

For many cases in drying, the heat-transfer coefficient can be expressed as

$$h_c = \alpha G^n / D_c p \tag{12-41}$$

where h_c = heat-transfer coefficient, J/(m^2·s·K)[Btu/(h·ft^2·°F)]; G = mass velocity of drying gas, kg/(s·m^2)[lb/(h·ft^2)]; D_c = characteristic dimension of the system, m; and α, n, and p are empirical constants. When radiation and conduction effects are negligible, the constant rate of drying from a surface is thus given by the following heat-transfer expression derived from Eqs. (12-26) and (12-41):

$$dw/d\theta = (\alpha G^n A/\lambda D_c^m)(t - t_s') \qquad (12\text{-}42)$$

When the liquid is water and the drying gas is air, t_s' is the wet-bulb temperature.

In order to estimate drying rates from Eq. (12-42) values of the empirical constants are required for the particular geometry under consideration. For flow parallel to plane plates, exponent n has been reported to range from 0.35 to 0.8 [Chu, Lane, and Conklin, *Ind. Eng. Chem.*, **45,** 1856 (1953); Wenzel and White, *Ind. Eng. Chem.*, **51,** 275 (1958)]. The differences in exponent have been attributed to differences in flow pattern in the space above the evaporating surface. In the absence of applicable specific data, the heat-transfer coefficient for the parallel-flow case can be taken, for estimating purposes, as

$$h = 8.8G^{0.8}/D_c^{0.2} \qquad (12\text{-}43)$$

where the experimental data have been weighted in favor of an exponent of 0.8 in conformity with the usual Colburn j factor and average values of the properties of air at 370 K have been incorporated.

Experimental data for drying from flat surfaces have been correlated by using the equivalent diameter of the flow channel or the length of the evaporating surface as the characteristic length dimension in the Reynolds number. However, the validity of one versus the other has not been established. The proper equivalent diameter probably depends at least on the geometry of the system, the roughness of the surface, and the flow conditions upstream of the evaporating surface. For most tray-drying calculations, the equivalent diameter (4 times the cross-sectional area divided by the perimeter of the flow channel) should be used.

For air flow impinging normally to the surface from slots, nozzles, or perforated plates, the heat-transfer coefficient can be obtained from the data of Friedman and Mueller (*Proceedings of the General Discussion on Heat Transfer,* Institution of Mechanical Engineers, London, and American Society of Mechanical Engineers, New York, 1951, pp. 138–142). These investigators give

$$h_c = \alpha G^{0.78} \qquad (12\text{-}44)$$

where the gas mass velocity G is based on the total heat-transfer area and α is dependent on the plate open area, hole or slot size, and spacing between the plate, nozzle, or slot and the heat-transfer surface.

Most efficient performance is obtained with plates having open areas equal to 2 to 3 percent of the total heat-transfer area. The plate should be located at a distance equal to four to six hole (or equivalent) diameters from the heat-transfer surface.

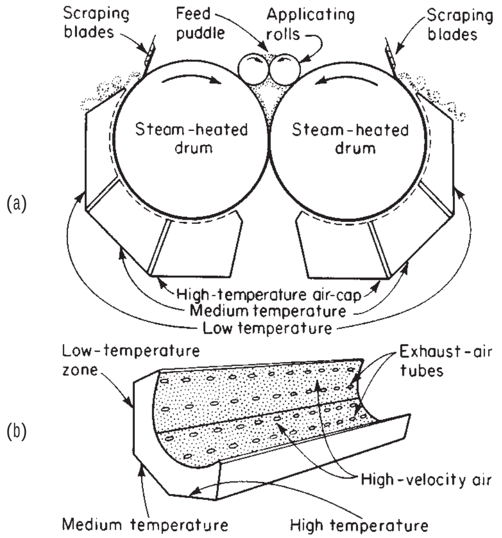


FIG. 12-46 Example of the use of air impingement in drying as a secondary heat source on a double-drum dryer. [Chem. Eng., *197,* (*June 19, 1967*).]

Data from tests employing multiple slots, with a correction calculated for slot width, were reported by Korger and Kizek [*Int. J. Heat Mass Transfer,* London, **9,** 337 (1966)].

Air impingement is commonly employed for drying sheets, film, thin slabs, and coatings. Another application in which it is used is as a secondary heat source on drum and can dryers (see Fig. 12-46).

Determination of the Temperature of the Evaporating Surface in Direct-Heat Tray Dryers When radiation and conduction are negligible, the temperature of the evaporating surface approaches the wet-bulb temperature and is readily obtained from the humidity and dry-bulb temperature. Frequently, however, radiation and conduction cause the temperature of the evaporating surface to exceed the wet-bulb temperature. When this occurs, the true surface temperature must be estimated.

Under steady-state conditions the temperature of the evaporating surface increases until the rate of sensible heat transfer to the surface equals the rate of heat removed by evaporation from the surface. To calculate this temperature, it is convenient to modify Eq. (12-26) in terms of humidity rather than partial-pressure difference, as follows:

$$k_g(p_s - p) = k'(H_s - H) \qquad (12\text{-}45)$$

where k' = mass-transfer coefficient, kg/(s·m^2)(unit humidity difference), and $k' = pk_g(M_a/M_w)$ is a suitable approximation at low humidities; k_g = mass-transfer coefficient, kg/(s·m^2·atm); M_a = molecular weight of air; M_w = molecular weight of the diffusing vapor; p_s = vapor pressure of the liquid at the temperature of the evaporating surface, atm; p = partial pressure of vapor in air, atm; H_s = saturation humidity of the air at the temperature of the drying surface, kg/kg dry air; H = humidity of the drying air, kg/kg dry air; and p = total pressure, atm. For air-water mixtures k' is approximately 1.6 k_g at atmospheric pressure.

A rate balance between evaporation and heat transfer when radiation occurs may be modified by means of the psychrometric ratio for air-water vapor mixtures to give:

$$\frac{\lambda}{C_s}(H_s - H) = (t - t_s') + \frac{h_t\epsilon}{h_c}(t_r - t_s') \qquad (12\text{-}46)$$

where λ = latent heat of evaporation, J/kg at t_s'; $C_s = h_c/k'$, where h_c = convection heat-transfer coefficient, J/(s·m^2·K), and C_s = heat capacity of humid air, J/(kg dry air·K), as defined in the subsection "Application of Psychrometry to Drying"; t = temperature of drying gases, K; t_s' = temperature of the wet surface, K; h_c = radiation heat-transfer coefficient, J/(s·m^2·K); h_c = convection heat-transfer coefficient, J/(s·m^2·K); t_r = temperature of source radiating heat to the wet surface, K; and ϵ = emissivity of surface receiving radiation.

Equation (12-46) may be solved by trial and error or graphically to estimate the true values of H_s and t_s' and, hence, the actual drying rate. The values of λ and h_r depend on the value of t_s' but can generally be considered constant over the range of temperatures usually encountered in air drying.

Frequently, particularly in tray drying, heat arrives at the evaporating surface from the tray walls by conduction through the wet material. For this case, in which both radiation and conduction are significant, the total heat-transfer coefficient is given by Shepherd, Brewer, and Hadlock [*Ind. Eng. Chem.*, **30,** 388 (1938)] as

$$h_t = (h_c + h_r)\left[1 + \frac{A_u}{1 + d(h_c + h_r)/k}\right] \qquad (12\text{-}47)$$

where h_t = total heat-transfer coefficient, J/(s·m^2·K); A_u = ratio of outside unwetted surface to evaporating surface area; d = depth of material in tray, m; and k = thermal conductivity of the wet material, J/[(s·m^2)(K/m)]. Note that h_c must be corrected for emissivity of the surface. For insulated trays, the arithmetic average of inside and outside unwetted area should be used.

Equation (12-47) assumes that all heat sources are at the same temperature and that the convection coefficients to the evaporating surface and to the unwetted portions of the tray are equal. When radiation occurs from a source at a different temperature, the radiation coefficient can be corrected to the same basis by multiplying by the ratio $(t - t_s')/(t_r - t_s')$, where t, t_s', and t_r are the drying-gas, evaporating-surface, and radiator temperatures respectively.

A relationship for estimating the surface temperature t'_s, based on the use of Eq. (12-47) to determine h_t, is as follows:

$$(H_s - H) = (h_t C_s/\lambda h_c)(t - t'_s) \qquad (12\text{-}48)$$

Equation (12-48) can be solved numerically or graphically. Figure 12-47 indicates how H_s and t'_s may be determined graphically on a humidity chart by the point of intersection on the saturation-humidity curve of a straight line of slope $h_t C_s/\lambda h_c$ passing through point (H_s, t_s).

Performance Data for Direct-Heat Tray Dryers A standard two-truck dryer is illustrated in Fig. 12-48. Adjustable baffles or a perforated distribution plate is normally employed to develop 0.3 to 1.3 cm of water-pressure drop at the wall through which air enters the truck enclosure. This will enhance the uniformity of air distribution, from top to bottom, among the trays. In three (or more) truck ovens, air-reheat coils may be placed between trucks if the evaporative load is high. Means for reversing air-flow direction may also be provided in multiple-truck units.

Performance data on some typical tray and compartment dryers are tabulated in Table 12-10. These indicate that an overall rate of evaporation of 0.0025 to 0.025 kg water/(s·m^2) of tray area may be expected from tray and tray-truck dryers. The thermal efficiency of this type of dryer will vary from 20 to 50 percent, depending on the drying temperature used and the humidity of the exhaust air. In drying to very low moisture contents under temperature restrictions, the thermal efficiency may be in the order of 10 percent. The major operating cost for a tray dryer is the labor involved in loading and unloading the trays. About two labor-hours are required to load and unload a standard two-truck tray dryer. In addition, about one-third to one-fifth of a worker's time is required to supervise the dryer during the drying period. Power for tray and compartment dryers will be approximately 1.1 kW per truck in the dryer. Maintenance will run from 3 to 5 percent of the installed cost per year.

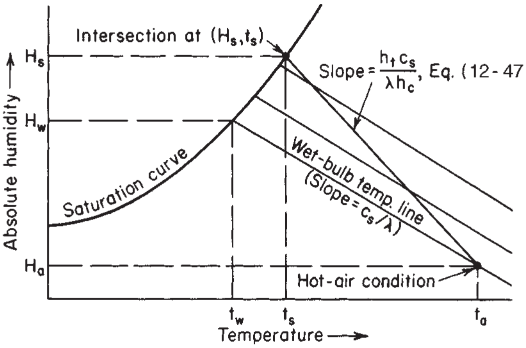


FIG. 12-47 Graphical estimation of surface temperature during constant-rate period.

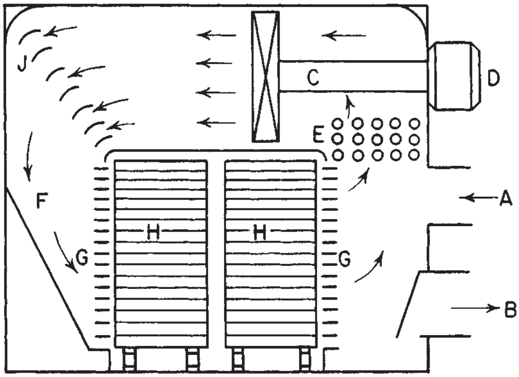


FIG. 12-48 Double-truck dryer. (*A*) Air-inlet duct. (*B*) Air-exhaust duct with damper. (*C*) Adjustable-pitch fan 1 to 15 hp. (*D*) Fan motor. (*E*) Fin heaters. (*F*) Plenum chamber. (*G*) Adjustable air-blast nozzles. (*H*) Trucks and trays. (*J*) Turning vanes.

BATCH THROUGH-CIRCULATION DRYERS

In one type of batch through-circulation dryer, heated air passes through a stationary permeable bed of the wet material placed on removable screen-bottom trays suitably supported in the dryer. This type is similar to a standard tray dryer except that hot air passes through the wet solid instead of across it. The pressure drop through the bed of material does not usually exceed about 2 cm of water. In another type, deep perforated-bottom trays are placed on top of plenum chambers in a closed-circuit hot-air-circulating system. In some food-drying plants, the material is placed in finishing bins with perforated bottoms; heated air passes up through the material and is removed from the top of the bin, reheated, and recirculated. The latter types involve a pressure drop through the bed of material of 1 to 8 cm of water at relatively low air rates. Table 12-11 gives performance data on three applications of batch through-circulation dryers. Batch through-circulation dryers are restricted in application to granular materials that permit free flow-through circulation of air. Drying times are usually much shorter than in parallel-flow tray dryers. Design methods are included in the subsection "Continuous Through-Circulation Dryers."

Vacuum-Shelf Dryers Vacuum-shelf dryers are indirect-heated batch dryers consisting of a vacuumtight chamber usually constructed of cast iron or steel plate, heated, supporting shelves within the chamber, a vacuum source, and usually a condenser. One or two doors are provided, depending on the size of the chamber. The doors are sealed with resilient gaskets of rubber or similar material (Fig. 12-49).

Hollow shelves of flat steel plate are fastened permanently inside the vacuum chamber and are connected in parallel to inlet and outlet headers. The heating medium, entering through one header and passing through the hollow shelves to the exit header, is generally steam, ranging in pressure from 700 kPa gauge to subatmospheric pressure for low-temperature operations. Low temperatures can be provided by circulating hot water, and high temperatures can be obtained by circulating hot oil or Dowtherm. Some small dryers employ electrically heated shelves. The material to be dried is placed in pans or trays on the heated shelves. The trays are generally of metal to ensure good heat transfer between the shelf and the tray.

Vacuum-shelf dryers may vary in size from 1 to 24 shelves, the largest chambers having overall dimensions of 6 m wide, 3 m long, and 2.5 m high.

Vacuum is applied to the chamber and vapor is removed through a large pipe which is connected to the chamber in a manner such that, if the vacuum is broken suddenly, the inrushing air will not greatly disturb the bed of material being dried. This line leads to a condenser where moisture or solvent that has been vaporized is condensed. The noncondensable exhaust gas goes to the vacuum source, which may be a wet or dry vacuum pump or a steam-jet ejector.

Vacuum-shelf dryers are used extensively for drying pharmaceuticals, temperature-sensitive or easily oxidizable materials, and materials so valuable that labor cost is insignificant. They are particularly useful for handling small batches of materials wet with toxic or valuable solvents. Recovery of the solvent is easily accomplished without danger of passing through an explosive range. Dusty materials may be dried with negligible dust loss. Hygroscopic materials may be completely dried at temperatures below that required in atmospheric dryers. The equipment is employed also for freeze-drying processes, for metallizing-furnace operations, and for the manufacture of semiconductor parts in controlled atmospheres. All these latter processes demand much lower operating pressures than do ordinary drying operations.

Design Methods for Vacuum-Shelf Dryers Heat is transferred to the wet material by conduction through the shelf and bottom of the tray and by radiation from the shelf above. The critical moisture content will not be necessarily the same as for atmospheric tray drying [Ernst, Ridgway, and Tiller, *Ind. Eng. Chem.*, **30,** 1122 (1938)].

TABLE 12-10 Manufacturer's Performance Data for Tray and Tray-Truck Dryers*

Material	Color	Chrome yellow	Toluidine red	Half-finished Titone	Color
Type of dryer	2-truck	16-tray dryer	16-tray	3-truck	2-truck
Capacity, kg product/h	11.2	16.1	1.9	56.7	4.8
Number of trays	80	16	16	180	120
Tray spacing, cm	10	10	10	7.5	9
Tray size, cm	60 × 75 × 4	65 × 100 × 2.2	65 × 100 × 2	60 × 70 × 3.8	60 × 70 × 2.5
Depth of loading, cm	2.5 to 5	3	3.5	3	
Initial moisture, % bone-dry basis	207	46	220	223	116
Final moisture, % bone-dry basis	4.5	0.25	0.1	25	0.5
Air temperature, °C	85–74	100	50	95	99
Loading, kg product/m^2	10.0	33.7	7.8	14.9	9.28
Drying time, h	33	21	41	20	96
Air velocity, m/s	1.0	2.3	2.3	3.0	2.5
Drying, kg water evaporated/($h \cdot m^2$)	0.59	65	0.41	1.17	0.11
Steam consumption, kg/kg water evaporated	2.5	3.0	—	2.75	
Total installed power, kW	1.5	0.75	0.75	2.25	1.5

*Courtesy of Proctor & Schwartz, Inc.

During the constant-rate period, moisture is rapidly removed. Often 50 percent of the moisture will evaporate in the first hour of a 6- to 8-h cycle. The drying time has been found to be proportional to between the first and second power of the depth of loading. Shelf vacuum dryers operate in the range of 1 to 25 mmHg pressure. For size-estimating purposes, a heat-transfer coefficient of 20 J/($m^2 \cdot s \cdot K$) may be used. The area employed in this case should be the shelf area in direct contact with the trays. Trays should be maintained as flatly as possible to obtain maximum area of contact with the heated shelves. For the same reason, the shelves should be kept free from scale and rust. Air vents should be installed on steam-heated shelves to vent noncondensable gases. The heating medium should not be applied to the shelves until after the air has been evacuated from the chamber in order to reduce the possibility of the material's overheating or boiling at the start of drying. Casehardening can sometimes be avoided by retarding the rate of drying in the early part of the cycle.

Performance Data for Vacuum-Shelf Dryers The purchase price of a vacuum-shelf dryer depends upon the cabinet size and number of shelves per cabinet. For estimating purposes, typical prices (1985) and auxiliary-equipment requirements are given in Table 12-12. Installed cost of the equipment will be roughly 100 percent of the carbon steel purchase cost.

The thermal efficiency of a vacuum-shelf dryer is usually on the order of 60 to 60 percent. Table 12-13 gives operating data for one organic color and two inorganic compounds. Labor may constitute 50 percent of the operating cost; maintenance, 20 percent. Annual maintenance costs amount to 5 to 10 percent of the total installed cost. Actual labor costs will depend on drying time, facilities for loading and unloading trays, etc. The power required for these dryers is only that for the vacuum system; for vacuums of 680 to 735 mmHg the power requirements are in the order of 0.06 to 0.12 kW/m^2 tray surface.

TABLE 12-11 Performance Data for Batch Through-Circulation Dryers*

Kind of material	Granular polymer	Vegetable	Vegetable seeds
Capacity, kg product/h	122	42.5	27.7
Number of trays	16	24	24
Tray spacing, cm	43	43	43
Tray size, cm	91.4 × 104	91.4 × 104	85 × 98
Depth of loading, cm	7.0	6	4
Physical form of product	Crumbs	0.6-cm diced cubes	Washed seeds
Initial moisture content, % dry basis	11.1	669.0	100.0
Final moisture content, % dry basis	0.1	5.0	9.9
Air temperature, °C	88	77 dry-bulb	36
Air velocity, superficial, m/s	1.0	0.6 to 1.0	1.0
Tray loading, kg product/m^2	16.1	5.2	6.7
Drying time, h	2.0	8.5	5.5
Overall drying rate, kg water evaporated/($h \cdot m^2$)	0.89	11.86	1.14
Steam consumption, kg/kg water evaporated	4.0	2.42	6.8
Installed power, kW	7.5	19	19

*Courtesy of Proctor & Schwartz, Inc.

Batch Furnaces, Other Furnace Types, and Kilns Batch furnaces are employed mainly for the heat treating of metals, such as annealing, normalizing, and "drawing" (tempering), and for the drying and calcination of ceramic articles. Many specialized furnaces have been designed for these purposes and may be either batch or continuous in operation. Batch furnaces are used in chemical processing for the same purposes as batch tray and truck dryers, when the drying or process temperature exceeds that which can be tolerated by unlined metal walls; ordinary tray and truck dryers are rarely employed when the circulating-gas temperature will exceed 600 to 700 K. They are employed for small-batch calcination, thermal decompositions, and other chemical reactions; these are the same as those reactions performed on a larger scale in rotary kilns, hearth furnaces, and shaft furnaces.

Design procedures and information on heat release in furnaces are given in Sec. 11. Tables indicating normal operating temperatures in various heating furnaces and the more common process furnaces are also included. Specialized designs of batch furnaces are shown in Figs. 12-50 to 12-53 and are described briefly in the following paragraphs. All may be heated by gas, oil, or electricity. **Standard oven furnaces** are similar in design to the small muffle furnace depicted in Fig. 12-53, but with the muffle housing eliminated.

Forced-convection pit furnaces are employed for heat-treating small metal parts in bulk. Small pieces are suspended in a mesh-bottom basket, while larger pieces are placed on racks. Air heating is by means of Nichrome electric coils set in refractory walls around the periphery of the pit. A high-velocity fan beneath the basket circulates heated air up past the coils and then down through the basket. Some heat is radiated to the outer basket shell, but most is transferred by direct convection from the circulating gas to the solids.

Car-bottom furnaces differ from standard types in that the charge is placed upon movable cars for running into the furnace enclosure. The top of the car is refractory-lined and forms the furnace hearth. The top only is exposed to heat, the lower metal structure being protected by the hearth brick, sand, and water seals at the sides and ends and by the circulation of cooling air around the car structure below the hearth. For use where floor space is limited **elevator furnaces** serve similar purposes.

The **rotary-hearth furnace** consists of a heating chamber lined with refractory brick within which is an annular-shaped refractory-lined rotating hearth. Around the periphery of the rotating hearth, sand or circulating liquid seals are employed to prevent air infiltration. It can be made semicontinuous in operation. The hearth speed can be

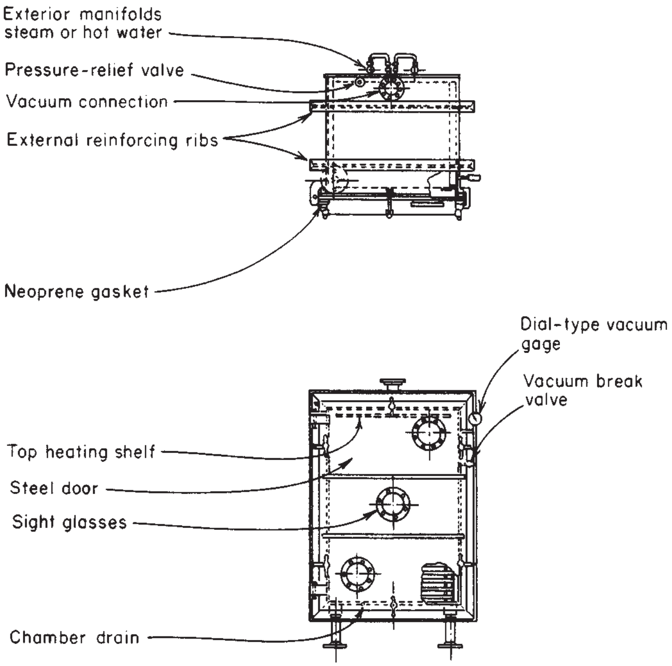


FIG. 12-49 Vacuum-shelf dryer. (*Stokes Equipment Division, Pennwalt Corp.*)

TABLE 12-12 Standard Vacuum-Shelf Dryers*

Shelf area, m^2	Floor space, m^2	Weight average, kg	Pump capacity, m^3/s	Pump motor, kW	Condenser area, m^2	Price/m^2 (1995) Carbon steel	Price/m^2 (1995) 304 stainless steel
0.4–1.1	4.5	540	0.024	1.12	1	$110	$170
1.1–2.2	4.5	680	0.024	1.12	1	75	110
2.2–5.0	4.6	1130	0.038	1.49	4	45	65
5.0–6.7	5.0	1630	0.038	1.49	4	36	65
6.7–14.9	6.4	3900	0.071	2.24	9	27	45
16.7–21.1	6.9	5220	0.071	2.24	9	22	36

*Stokes Vacuum, Inc.

varied to meet changing requirements in size, weight, and load of the charge. For gas and oil heating, the burners fire from the sides of the chamber, tangentially to the hearth.

Standard furnaces are usually direct-heated, in that the burner combustion gases circulate directly over the charge; occasionally the flame may be permitted to impinge on the charge. For bright annealing, tool hardening, powdered-metal sintering, and other work requiring protection of the charge by special atmospheres, **muffle-type furnaces** are frequently employed. In these, the charge is separated from the burners and combustion gases by a refractory arch. Heat is transferred by hot-gas radiation and convection to the arch and by radiation from the arch to the charge.

TABLE 12-13 Performance Data of Vacuum-Shelf Dryers

Material	Sulfur black	Calcium carbonate	Calcium phosphate
Loading, kg dry material/m^2	25	17	33
Steam pressure, kPa gauge	410	410	205
Vacuum, mmHg	685–710	685–710	685–710
Initial moisture content, % (wet basis)	50	50.3	30.6
Final moisture content, % (wet basis)	1	1.15	4.3
Drying time, h	8	7	6
Evaporation rate, kg/(s·m^2)	8.9×10^{-4}	7.9×10^{-4}	6.6×10^{-4}

When used for **ceramic heating,** furnaces are called kilns. Operations include drying, oxidation, calcination, and vitrification. These kilns employ horizontal space burners with gaseous, liquid, or solid fuels. If product quality is not injured, ceramic ware may be exposed to flame and combustion gases; otherwise, muffle kilns are employed. Dutch ovens are used frequently for heat generation.

Downdraft kilns are the most common type, being used for brick, pipe, tile, and stoneware. The name is derived from the direction of combustion-gas flow when contacting the charge. The gases then flow up inside the walls to the top of the kiln and chimney. **Updraft kilns** are similar except in direction of gas flow, which is upward past the charge. They are employed commonly for pottery burning. **Stove kilns** are variations of updraft kilns used for burning common brick. The kiln is built of green brick and covered with a layer of burned brick. It is completely dismantled after each burning. **Clamp kilns** are another variation of updraft kilns used for common brick and temporary in nature. They have no tops or flue systems but consist only of sidewalls with arched spaces for combustion.

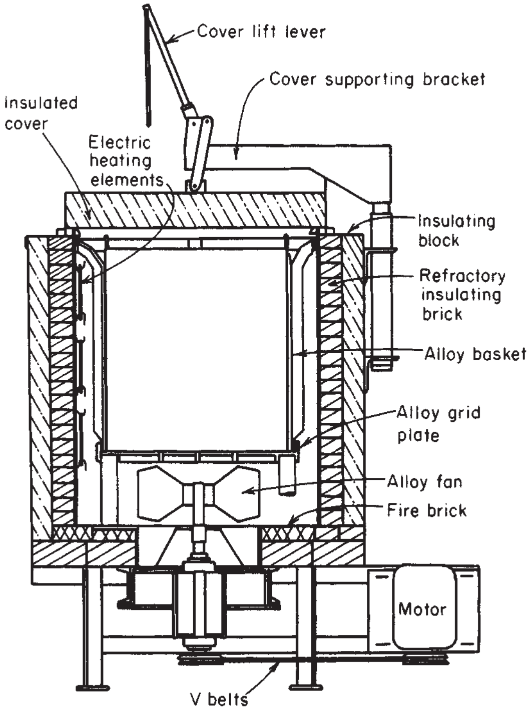


FIG. 12-50 Pit furnace. (*W. S. Rockwell Co.*)

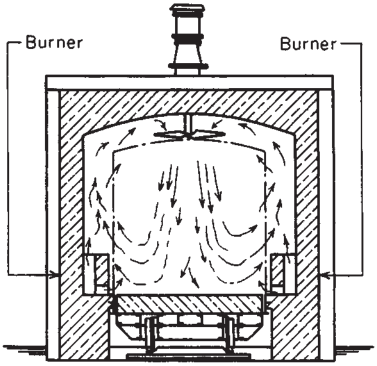


FIG. 12-51 Car-bottom furnace. (*W. S. Rockwell Co.*)

CONTINUOUS TUNNEL DRYERS

Continuous tunnels are in many cases **batch truck** or **tray compartments, operated in series.** The solids to be processed are placed in trays or on trucks which move progressively through the tunnel in contact with hot gases. Operation is **semicontinuous;** when the tunnel is filled, one truck is removed from the discharge end as each new truck is fed into the inlet end. In some cases, the trucks move on tracks or monorails, and they are usually conveyed mechanically, employing chain drives connecting to the bottom of each truck. Schematic diagrams of three typical tunnel arrangements are shown in Fig. 12-54. **Belt-conveyor and screen-conveyor tunnels are truly continuous** in operation, carrying a layer of solids on an endless conveyor.

Air flow can be totally **cocurrent, countercurrent,** or a combination of both as shown in Fig. 12-54. In addition, **cross-flow** designs are employed frequently, with the heating air flowing back and forth across the trucks in series. Reheat coils may be installed after each cross-flow pass to maintain constant-temperature operation; large propeller-type circulating fans are installed at each stage, and air may be introduced or exhausted at any desirable points. Tunnel equipment possesses maximum flexibility for any combination of air flow and temperature staging. When handling granular, particulate solids which do not offer high resistance to air flow, perforated or screen-type belt conveyors are employed with **through circulation** of gas to improve heat- and mass-transfer rates.

In tunnel equipment, the solids are usually heated by direct contact with hot gases. In high-temperature operations, radiation from walls and refractory lining may be significant also. The air in a direct-heat unit may be heated directly or indirectly by combustion or, at temperature below 475 K, by finned steam coils.

Applications of tunnel equipment are essentially the same as for batch tray and compartment units previously described, namely, practically all forms of particulate solids and large solid objects. In operation, they are more suitable for large-quantity production, usually representing investment and installation savings over (multiple) batch compartments. In the case of truck and tray tunnels, labor savings for loading and unloading are not significant compared with batch equipment. Belt and screen conveyors which are truly continuous represent major labor savings over batch operations but require additional investment for automatic feeding and unloading devices.

Auxiliary equipment and the special design considerations discussed for batch trays and compartments apply also to tunnel equipment. For size-estimating purposes, tray and truck tunnels and furnaces can be treated in the same manner as discussed for batch equipment.

Continuous Through-Circulation 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. Dryer 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 conveying-screen dryer** in which wet material is conveyed as a layer, 2 to 15 cm deep, on a horizontal mesh screen or perforated apron, while heated air is blown either upward or downward through the bed of material. Its drying characteristics were studied by Marshall and Hougen [*Trans. Am. Inst. Chem. Eng.*, **38,** 91 (1942)]. 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. 12-55, 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. A portion of the air is exhausted continuously by one or two 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 into 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. 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.

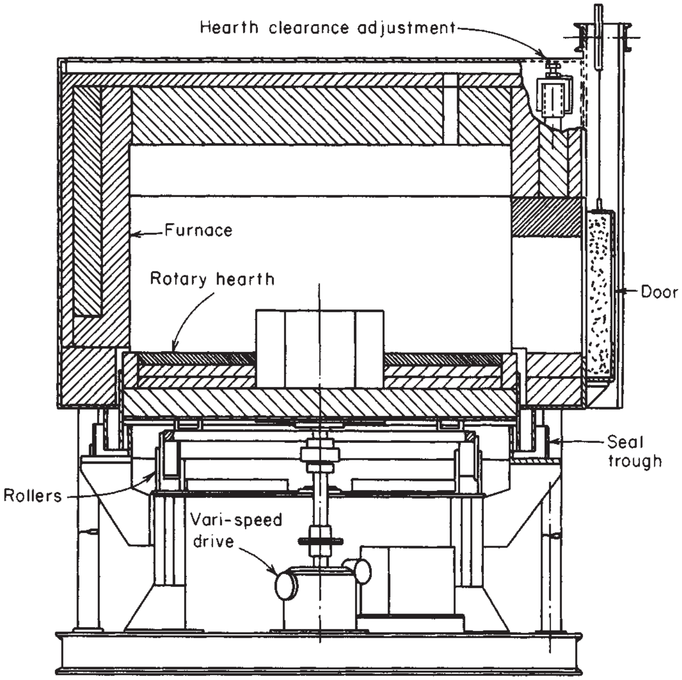


FIG. 12-52 Rotary-hearth furnace. (*W. S. Rockwell Co.*)

2. Pasty materials can often be preformed by extrusion to form sphaghetti-like 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 12-14 gives a list of materials classified by preforming methods suitable for through-circulation drying.

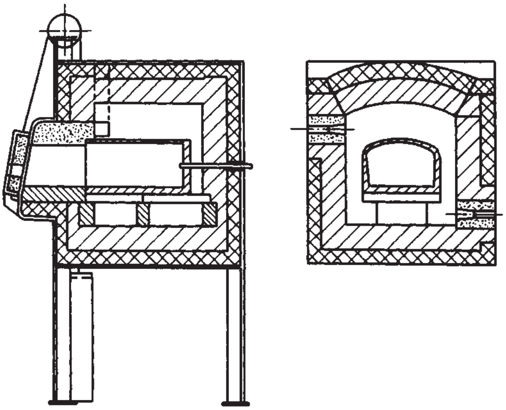


FIG. 12-53 Small muffle furnace. (*W. S. Rockwell Co.*)

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. Conveyors may be made of wire-mesh screen or perforated-steel plate. The minimum practical screen opening size is about 30 mesh.

Design Methods for Continuous Tunnel Dryers In actual practice, design of a continuous through-circulation dryer is best based upon data taken in pilot-plant tests. Loading and distribution of solids on the screen are rarely as nearly uniform in commercial installations as in test dryers; 50 to 100 percent may be added to the test drying time for commercial design.

A mathematical method of a through-circulation dryer has been developed by Thygeson [*Am. Inst. Chem. Eng. J.*, **16**(5), 749 (1970)]. Results obtained by Gamson, Thodos, and Hougen [*Trans. Am. Inst. Chem. Eng.*, **39,** 1 (1943)] and Wilke and Hougen [ibid., **41,** 444 (1945)] for the rates of adiabatic evaporation of water from packed beds of porous solids are applicable when drying gases flow upward to downward. Use of average additive properties of the drying gas leads to

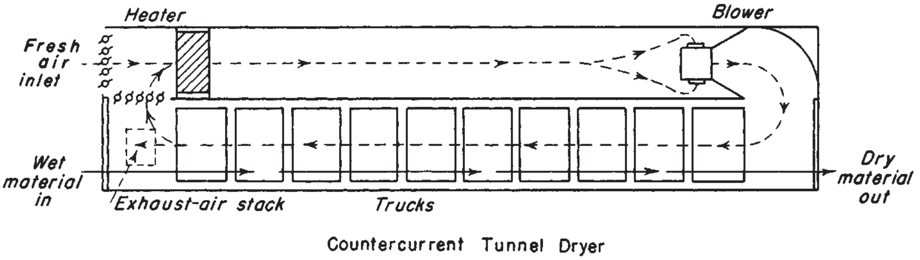
$$h_c = 0.11\,\frac{G^{0.59}}{D_p^{0.41}} \qquad \text{for} \qquad \frac{D_pG}{\mu} > 350 \tag{12-49}$$

and

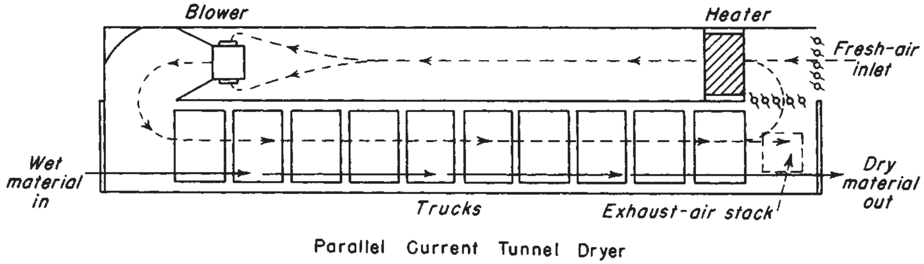
$$h_c = 0.15\,\frac{G^{0.49}}{D_p^{0.51}} \qquad \text{for} \qquad \frac{D_pG}{\mu} < 350 \tag{12-50}$$

where μ = gas viscosity, lb/(ft·h); D_p = diameter of sphere having the same surface area as particle, ft; and G = mass velocity of drying gas, lb/(h·ft^2) [to convert from pounds per foot-hour to newtons per second-square meter, multiply by 4.133×10^{-4}; to convert from feet to meters, multiply by 0.3048; and to convert from pounds per hour-square foot to kilograms per second-square meter, multiply by 1.3562×10^{-3}].

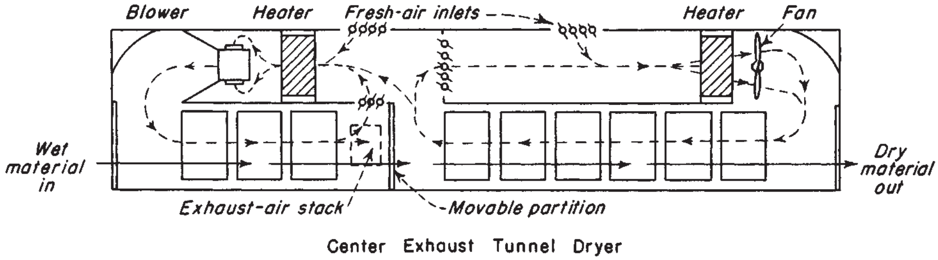
Performance and Cost Data for Continuous Tunnel Dryers Experimental performance data are given in Table 12-15 for numer-



(a) Countercurrent Tunnel Dryer



(b) Parallel Current Tunnel Dryer



(c) Center Exhaust Tunnel Dryer

FIG. 12-54 Three types of tunnel dryers. [*Van Arsdale,* Food Ind. ***14*** *(10), 43 (1942).*]

ous common materials. Performance data from several commercial through-circulation conveyor dryers are given in Table 12-16. Labor requirements vary depending on the time required for feed adjustments, inspection, etc. These dryers will consume from 0.9 to 1.1 kg of steam/kg of water evaporated. Thermal efficiency is a function of final moisture required and percent air recirculation.

Conveying-screen dryers are fabricated with conveyor widths from 0.3- to 4.4-m sections 1.6 to 2.5 m long. Each section consists of a sheet-metal enclosure, insulated sidewalls and roof, heating coils, a circulating fan, inlet-air distributor baffles, a fines catch pan under the conveyor, and a conveyor screeen (Fig. 12-56). Table 12-17 gives approximate purchase costs for equipment with type 304 stainless-steel hinged conveyor screens and includes steam-coil heaters, fans, motors, and a variable-speed conveyor drive. Cabinet- and auxiliary-equipment fabrication is of aluminized steel or stainless-steel materials. Prices do not include temperature controllers, motor starters, preform equipment, or auxiliary feed and discharge conveyors. These may add $55,000 to $135,000 to the dryer purchase cost (1995 costs).

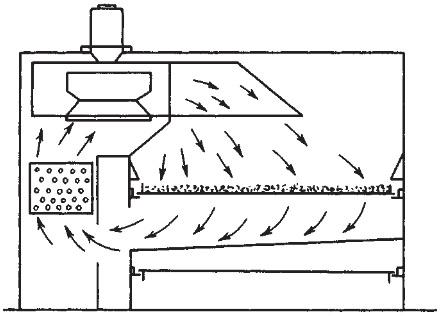


FIG. 12-55 Section view of a continuous through-circulation conveyor dryer. (*Proctor & Schwartz, Inc.*)

A continuous conveyor dryer employing a combination of air impingement and through circulation is shown in Fig. 12-57.

Continuous Furnaces Continuous furnaces are employed for the same general duties cited for batch furnaces. Units are gas, oil, or electrically heated and utilize direct circulation of combustion gases or muffles for heat transfer. Continuous furnaces frequently have an extension added for **cooling** the charge before exposure to atmospheric air.

Conveyors may be of parallel-chain, mat, slat, woven wire-mesh belt, or cast-alloy type. Automatic tensioning devices are used to maintain belt tension during heating and cooling. The product may rest directly on the conveyor or on special supports built into it. Roller-conveyors are used for large pieces. **Flame curtains** are provided for sealing the ends and for protection of special treating atmospheres.

The pusher-type furnace is relatively free from mechanical problems because all mechanical parts are located outside the hot zone. It employs a roller-conveyor usually and will handle charges weighing considerably more per square meter than a belt-conveyor furnace. Pushers are driven by electric motors, compressed air, or hydraulic systems and can be automatically timed and synchronized with door-

TABLE 12-14 Methods of Preforming Some Materials for Through-Circulation Drying

No preforming required	Scored on filter	Granulation	Extrusion	Finned drum	Flaking on chilled drum	Briquetting and squeezing
Cellulose acetate	Starch	Kaolin	Calcium carbonate	Lithopone	Soap flakes	Soda ash
Silica gel	Aluminum hydrate	Cryolite	White lead	Zinc yellow		Cornstarch
Scoured wool		Lead arsenate	Lithopone	Calcium carbonate		Synthetic rubber
Sawdust		Cornstarch	Titanium dioxide	Magnesium carbonate		
Rayon waste		Cellulose acetate	Magnesium carbonate			
Fluorspar		Dye intermediates	Aluminum stearate			
Tapioca			Zinc stearate			
Breakfast food						
Asbestos fiber						
Cotton linters						
Rayon staple						

TABLE 12-15 Experimental Through-Circulation Drying Data for Miscellaneous Materials

Material	Physical form	Moisture contents, kg/kg dry solid			Inlet-air temperature, K	Depth of bed, cm	Loading, kg product/m^2	Air velocity, m/s × 10^1	Experimental drying time, s × 10^{-2}
		Initial	Critical	Final					
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

TABLE 12-16 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
			Stage A,	Stage B			
Approximate dryer area, m^2	22.11	66.42	57.04	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/($h \cdot m^2$)	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 Proctor & Schwartz, Inc.

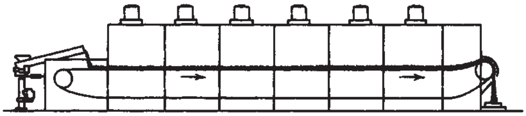


FIG. 12-56 Section assembly of a continuous through-circulation conveyor dryer. (*Proctor & Schwartz, Inc.*)

TABLE 12-17 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.

opening timers. For small solids, trays of perforated metal alloys are used to carry the product. These carriers ride through the tunnel on rollers, skid rails, and occasionally refractory skids, one tray pushing the next ahead. The charge may travel in a straight line or in counterflow movement in single or multiple chambers.

In counterflow movement, heat from the outgoing solids is transferred directly to cold incoming solids, reducing heat losses and fuel requirements. Continuous conveyor ovens are employed also for drying refractory shapes and for drying and baking enameled pieces. In many of these latter, the parts are suspended from overhead chain conveyors.

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 has 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.*

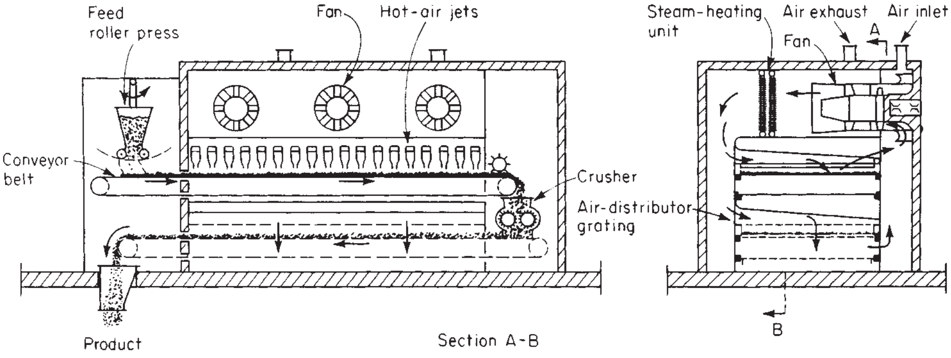


FIG. 12-57 Special conveyor dryer with air jets impinging on surface of bed on first pass. Dried material is crushed and passed again through dryer, with air going through the now-permeable bed. [Chem. Eng., 192 (*June 19, 1967*).]

ROTARY DRYERS

Description A rotary dryer consists of a cylinder, rotated upon suitable bearings and usually slightly inclined to the horizontal. The length of the cylinder may range from 4 to more than 10 times its diameter, which may vary from less than 0.3 to more than 3 m. Feed solids fed into one end of the cylinder progress through it by virtue of rotation, head effect, and slope of the cylinder and discharge as finished product at the other end. Gases flowing through the cylinder may retard or increase the rate of solids flow, depending upon whether gas flow is countercurrent or cocurrent with solids flow.

Rotary dryers have been classified as **direct, indirect-direct, indirect,** and **special types.** The terms refer to the method of heat transfer, being "direct" when heat is added to or removed from the solids by direct exchange between flowing gas and solids and being "indirect" when the heating medium is separated from physical contact with the solids by a metal wall or tube.

Only totally direct and totally indirect types will be discussed extensively here, as it must be recognized that an infinite number of variations between the two are possible. Their operating characteristics when performing heat- and mass-transfer operations make them suitable for the accomplishment of drying, chemical reactions, solvent recovery, thermal decompositions, mixing, sintering, and agglomeration of solids. The specific types included are the following:

Direct rotary dryer (cooler). This is usually a bare metal cylinder, with or without flights. It is suitable for low- and medium-temperature operations, the operating temperature being limited primarily by the strength characteristics of the metal employed in fabrication.

Direct rotary kiln. This is a metal cylinder lined on the interior with insulating block and/or refractory brick. It is suitable for high-temperature operations.

Indirect steam-tube dryer. This is a bare metal cylinder provided with one or more rows of metal tubes installed longitudinally in the shell. It is suitable for operation up to available steam temperatures or in processes requiring water cooling of the tubes.

Indirect rotary calciner. This is a bare metal cylinder surrounded on the outside by a fired or electrally heated furnace. It is suitable for operation at medium temperatures up to the maximum which can be tolerated by the metal wall of the cylinder, usually 650 to 700 K for carbon steel and 800 to 1025 K for stainless steel.

Direct Roto-Louvre dryer. This is one of the more important special types, differing from the direct rotary unit in that true *through circulation* of gas through the solids bed is provided. Like the direct rotary, it is suitable for low- and medium-temperature operation.

Field of Application Rotating equipment is applicable to batch or continuous processing solids which are relatively free-flowing and granular when discharged as product. Materials which are not completely free-flowing in their feed condition are handled in a special manner, either by recycling a portion of final product and premixing with the feed in an external mixer to form a uniform granular feed to the process or by maintaining a bed of free-flowing product in the cylinder at the feed end and, in essence, performing a premixing operation in the cylinder itself. A properly designed recycle process will permit processing of many forms of slurry and solution feeds in rotating vessels. Direct rotary kilns and indirect calciners without internal flights or other obstructions are often provided with **hanging link chains.** These may serve as surfaces upon which material can accumulate until it is no longer sticky, at which time it will break off as a granular solid and continue its movement through the cylinder. **Scraper chains** may also be provided on indirect calciners to maintain clean internal walls.

As a general rule, the direct-heat units are the simplest and most economical in construction and are employed when direct contact between the solids and flue gases or air can be tolerated. Because the total heat load must be introduced or removed in the gas stream, large gas volumes and high gas velocities are usually required. The latter will be rarely less than 0.5 m/s in an economical design. Therefore, employment of direct rotating equipment with solids containing extremely fine particles is likely to result in excessive entrainment losses in the exit-gas stream.

The indirect forms require only sufficient gas flow through the cylinder to remove vapors or otherwise complete the internal process. In addition, these can be sealed for processes requiring special gas atmospheres and exclusion of outside air.

Auxiliary Equipment On direct-heat rotating equipment, a combustion chamber is required for high temperatures and finned steam coils are used for low temperatures. If contamination of the product with combustion gases is undesirable on direct-heat units, indirect gas- or oil-fired air heaters may be employed to achieve temperatures in excess of available steam.

The *method of feeding* rotating equipment depends upon material characteristics and the location and type of upstream processing equipment. When the feed comes from above, a chute extending into the cylinder may be employed. For sealing purposes or if gravity feed is not convenient, a screw feeder is normally used. On cocurrent direct-heat units, cold-water jacketing of the feed chute or conveyor may be desirable if it is contacted by the inlet hot-gas stream. This will prevent overheating of the metal wall with resultant scaling or overheating of heat-sensitive feed materials.

Any type of solids conveyor may be suitable for **recycle** mixing; however, the most universally applicable is the double-shaft pug-mill-type paddle mixer. This conveyor or mixer should be insulated to prevent excessive heat losses from the hot, dry recycle product. To ensure uniformity in the recycle operation, a **surge storage** reserve of recycle solids should be installed for startup purposes and in the event of interruption of product discharge from the cylinder. In recycle operations, 50 to 60 percent product recirculation is found economical in many instances.

One method of feeding direct cocurrent drying equipment utilizes dryer exhaust gases to convey, mix, and predry wet feed. The latter is added to the exhaust gases, at high velocity, from the dryer. The wet feed, mixed with dust entrained from the dryer, separates from the exhaust gases in a cyclone and drops into the feed end of the cylinder. The technique combines pneumatic and rotary drying. High thermal efficiency results from two cocurrent-flow stages operating countercurrently.

Pneumatic conveyors are frequently employed as both dry-product conveyors and coolers. Other types of cooling equipment often used are screw conveyors, vibrating conveyors, and direct or indirect rotating coolers.

Dust entrained in the exit-gas stream is customarily removed in cyclone collectors. This dust may be discharged back into the process or separately collected. For expensive materials or extremely fine particles, bag collectors may follow a cyclone collector, provided fabric temperature stability is not limiting. When toxic gases or solids are present, the exit gas is at a high temperature, the gas is close to saturation as from a steam-tube dryer, or gas recirculation in a sealed system is involved, wet scrubbers may be used independently or following a cyclone. Cyclones and bag collectors in drying applications frequently require insulation and steam tracing. The exhaust fan should be located downstream from the collection system.

Rotating equipment, except brick-lined vessels, operated above ambient temperatures is usually insulated to reduce heat losses. Exceptions are direct-heat units of bare metal construction operating at high temperatures, on which heat losses from the shell are necessary to prevent overheating of the metal. Insulation is particularly necessary on cocurrent direct-heat units. It is not unusual for product cooling or condensation on the shell to occur in the last 10 to 50 percent of the cylinder length if it is not well insulated.

For best operation, the feed rate to rotating equipment should be closely controlled and uniform in quantity and quality. Because solids temperatures are difficult to measure and changes slowly detected, most rotating-equipment operations are controlled by indirect means. Inlet and exit gas temperatures are measured and controlled on direct-heat units such as direct dryers and kilns, steam temperature and pressure and exit-gas temperature and humidity are controlled on steam-tube units, and direct shell temperature measurements are taken on indirect calciners. Product temperature measurements are taken for secondary control purposes only in most instances.

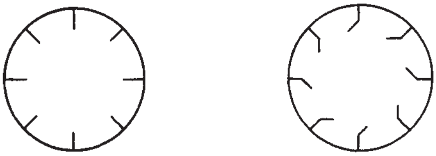
Equipment which is electrically driven and operated with metal temperatures exceeding 425 K should be provided with auxiliary drives or power sources. Loss of rotation of a heated calciner or high-temperature dryer carrying a heavy bed of hot solids will quickly result in sagging of the cylinder due to nonuniform cooling.

Direct-Heat Rotary Dryers The direct-heat rotary dryer is usually equipped with **flights** on the interior for lifting and showering the solids through the gas stream during passage through the cylinder. These flights are usually offset every 0.6 to 2 m to ensure more continuous and uniform curtains of solids in the gas. The shape of the flights depends upon the handling characteristics of the solids. For free-flowing materials, a radial flight with a 90° lip is employed. For sticky materials, a flat radial flight without any lip is used. When materials change characteristics during drying, the flight design is changed along the dryer length. Many standard dryer designs employ flat flights with no lips in the first one-third of the dryer measured from the feed end, flights with 45° lips in the middle one-third, and flights with 90° lips in the final one-third of the cylinder. **Spiral flights** are usually provided in the first meter or so at the feed end to accelerate forward flow from under the feed chute or conveyor and to prevent leakage over the feed-end retainer ring into the gas seals.

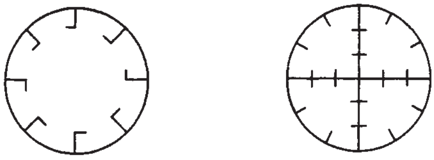
When cocurrent gas-solids flow is used, flights may be left out to the final meter or so at the exit end to reduce entrainment of dry product in the exit gas. Showering of wet feed at the feed end of a countercurrent dryer will, on the other hand, frequently serve as an effective means for scrubbing dry entrained solids from the gas stream before it leaves the cylinder. Some dryers are provided with sawtooth flights to obtain uniform showering, while others use lengths of chain, attached to the underside of the flights, to scrape over and knock the walls of the cylinder, thereby removing sticky solids which might normally adhere to it. In kilns, the chains may contribute significantly to heat transfer; however, their use contributes to maintenance costs when flights are present in direct dryers. Solids sticking on flights and walls are usually removed more efficiently by **external shell knockers.** In dryers of large cross section, internal elements or partitions are sometimes used to increase the effectiveness of material distribution and reduce dusting and impact grinding. Use of internal members increases the difficulty of cleaning and maintenance unless sufficient free area is left between partitions for easy access of a person. Some examples of the more common flight arrangements are shown in Fig. 12-58. Component arrangements of countercurrent direct rotary dryers are shown in Fig. 12-59, and those of a cocurrent unit in Fig. 12-60.

Countercurrent flow of gas and solids gives greater **heat-transfer efficiency** with a given inlet-gas temperature, but cocurrent flow can be used more frequently to dry heat-sensitive materials at higher inlet-gas temperatures because of the rapid cooling of the gas during initial evaporation of surface moisture.

A number of different methods are employed to seal the rotating cylinder and prevent gas leakage through the annular opening between the rotating cylinder and the stationary throat pieces. *None is an effective solids seal,* nor will any function satisfactorily as a gas seal if solids leakage over the retaining ring on the cylinder is permitted. Three examples of ordinary gas seals are shown in Fig. 12-61. On direct rotary dryers, few gas seals are intended to be completely gastight, but by careful control of the internal pressure, generally between 0.25 and 2.5 mm of water below atmosphere, dusting to the outside is prevented and in-leakage of outside air is minimized.


Radial flights

45-deg. lip flights


90-deg. lip flights

Shell with diaphragm section

FIG. 12-58 Alternative direct-heat rotary-dryer flight arrangements.

Figure 12-61 also illustrates three basic types of **trunnion roll-bearing assemblies.** Antifriction pillow blocks are the most common on modern dryers; however, when the dryer load requires larger than a 12.7- to 15.2-cm-diameter bearing on the trunnion shaft, the dead-shaft antifriction bearing is substituted. This represents a considerable cost saving compared with the larger pillow blocks. They are completely sealed and continuously bathed in lubricant. Pillow-block bushings are less often used. The thrust washers are difficult to seal against dust, and they draw more power. Thrust roll mountings are depicted also in Fig. 12-61. These are usually dead-shaft.

Gases are forced through the cylinder by either an exhauster or an exhauster-blower combination. With the latter arrangement it is possible to maintain very precise control of internal pressure even when the total system pressure drop is high. When a low-pressure-drop air heater is employed, however, the exhauster alone is usually sufficient, as the major gas pressure losses are found in the exit-air ductwork and dust collectors. Use of a blower by itself to force gas through the cylinder is an unusual practice, because the internal pressure is above atmospheric and hot air and dust may be blown into the gas seals or out into the surrounding working areas.

Special designs of direct rotary dryers, such as the Renneburg DehydrO-Mat (Edward Renneburg & Sons Co.), are constructed especially to provide lower retention during the falling-rate drying period for the escape of internal moisture from the solids. The DehydrO-Mat is a cocurrent dryer employing a small-diameter shell at the feed end, where rapid evaporation of surface moisture in the stream of initially hot gas is accomplished with low holdup. At the solids- and gas-exit end, the shell diameter is increased to reduce gas velocities and provide increased holdup for the solids while they are exposed to the partially cooled gas stream.

The Louisville type P dryer is a cocurrent dryer developed for the drying of heat-sensitive polymers. It is designed for use on rather finely divided and bulky materials which are easily airborne since its basic design utilizes a discharge cone permitting pneumatic conveying of dried solids from the dryer. Its internal design provides additional retention time by slowing the progress of the material through the dryer cylinder, permitting a comparatively high velocity of the drying medium without excessive blow-through.

The Louisville type H dryer is a modified cocurrent dryer with "flash-drying" characteristics. Its internal arrangements consist of alternating disks and doughnuts which give high differential velocities between the drying medium and the solids being processed to increase the heat transfer and hence the rate of moisture removal.

Design Methods for Direct-Heat Rotary Dryers Direct drying in a direct-heat rotary dryer is best expressed as a heat-transfer mechanism as follows:

$$Q_t = UaV(\Delta t)_m \tag{12-51}$$

where Q_t = total heat transferred, J/s; Ua = volumetric heat-transfer coefficient, J/(s·m^3·K); V = dryer volume, m^3; and $(\Delta t)_m$ = true mean temperature difference between the hot gases and material, K. When a considerable quantity of surface moisture is removed from the solids and the solids temperatures are unknown, a good approximation of $(\Delta t)_m$ is the logarithmic mean between the wet-bulb depressions of the drying air at the inlet and exit of the dryer.

Data for evaluating Ua were developed by Miller [*Trans. Am. Inst. Chem. Eng.,* **38,** 841 (1942)], Friedman and Marshall [*Chem. Eng. Prog.,* **45,** 482, 573 (1949)], and Seaman and Mitchell [*Chem. Eng. Prog.,* **50,** 467 (1954)]. These authors all employed relationships that could be reduced to the form $Ua = KG^n/D$, where K = a proportionality constant, G = gas mass velocity, D = diameter, and n = a constant.

P. Y. McCormick [*Chem. Eng. Prog.,* **58**(6), 57 (1962)] compared all available data. The comparisons showed that flight geometry and shell speed should be accounted for in the value of K. He suggested that shell rotational speed and flight number and shape must affect the overall balance; however, data for evaluating these variables separately are not available. Also, it is not believed that the effect of gas velocity

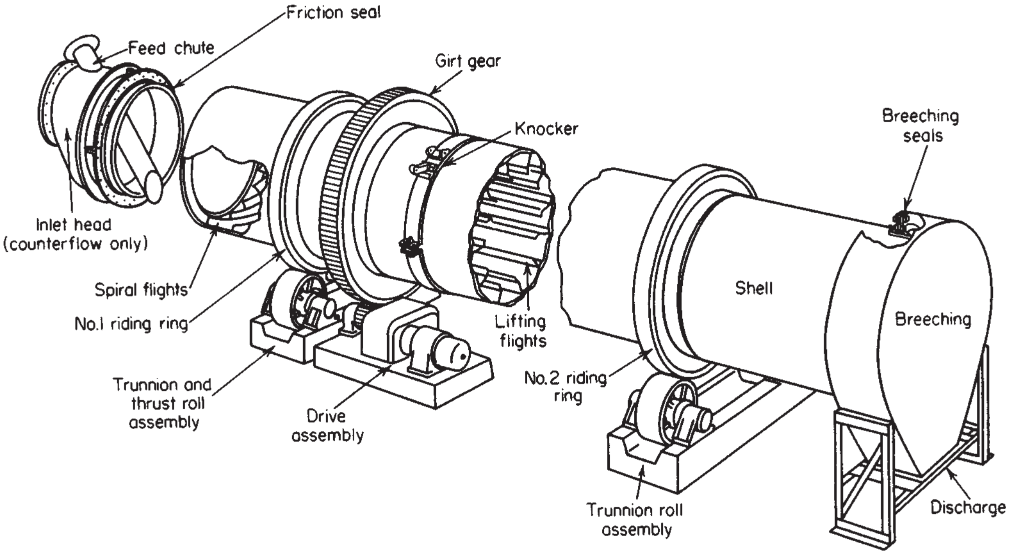


FIG. 12-59 Component arrangements of a countercurrent direct-heat rotary dryer. (*ABB Raymond/Bartlett-Snow TM.*)

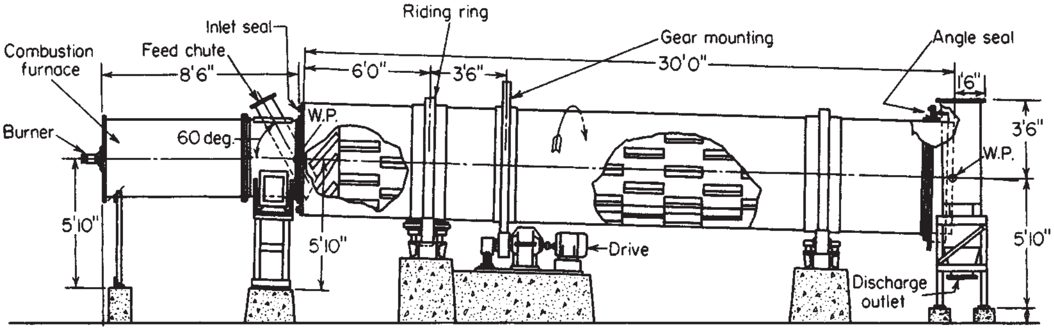


FIG. 12-60 Elevation of a 60-in-diameter by 30-ft-long direct-heat cocurrent rotary dryer. To convert inches to centimeters, multiply by 2.54; to convert feet to meters, multiply by 0.3048. (*ABB Raymond/Bartlett-Snow TM.*)

is toward reducing the surface film thickness around each particle; rather, an increase in gas velocity more likely breaks up more effectively the showering curtains of solids and thereby exposes more solids surface; i.e., the effect is to increase the a in Ua rather than U.

The following relationship is recommended for commercial dryers now manufactured in the United States, which usually have a flight count per circle of 2.4 to 3.0 D and operate at shell peripheral speeds of 60 to 75 ft/min:

$$Q_t = (0.5G^{0.67}/D)V\,\Delta t_m \tag{12-52}$$

$$= 0.4LDG^{0.67}\,\Delta t_m \tag{12-53}$$

where Q_t = total heat transferred, Btu/h; L = dryer length, ft; D = dryer diameter, ft; G = gas mass velocity, lb/(h·ft^2 of cross section); and Δt_m = log mean of the drying-gas wet-bulb depression at the inlet end and exit end of the dryer shell.

Typical operating data for cocurrent rotary dryers are given in Table 12-18. (Note that the driving force ΔT_m must be based on wet-bulb depression and not on material temperatures. Use of material temperatures, particularly when the dry solids are superheated after drying, will yield conservative results.)

In most cases, direct-heat rotary dryers are still sized on the basis of pilot-plant tests, because rarely is all the moisture to be removed truly "free" moisture, and residence time for diffusion is frequently needed. A theoretical model simulating the operation of both cocurrent and countercurrent rotary dryers which relies on pilot and bench scale tests to determine parameters which describe solids transport and drying rate is described by Papadakis, Langrish, Kemp, and Bahu [*Drying Technology—An International Journal,* **12**(1&2), 259 (1994)]. For maximum dryer heat-transfer efficiency, dryer fillage must be sufficient to load the lifting flights fully, as discussed later.

Unless material characteristics limit the gas temperature, the inlet temperature is usually fixed by the heating medium employed; i.e., 400 to 450 K for steam or 800 to 1100 K for gas- and oil-fired burners. The proper exit-gas temperature is largely an economic function. Its value may be determined as follows:

$$N_t = (t_1 - t_2)/(\Delta t)_m \tag{12-54}$$

where N_t = number of heat-transfer units based upon the gas; t_1 = initial-gas temperature, K; t_2 = exit-gas temperature allowing for heat losses, K; and $(\Delta t)_m$ is as defined for Eq. (12-51). Equation (12-54) can be used to select an exit-gas temperature since it has been found (empirically) that rotary dryers are most economically operated between N_t = 1.5 and N_t = 2.5.

The L/D (length-diameter) ratio found most efficient in commercial practice lies between 4 and 10. If the length calculated previously does not fall within these limits, another value of N_t which will place L/D in the proper range may be computed.

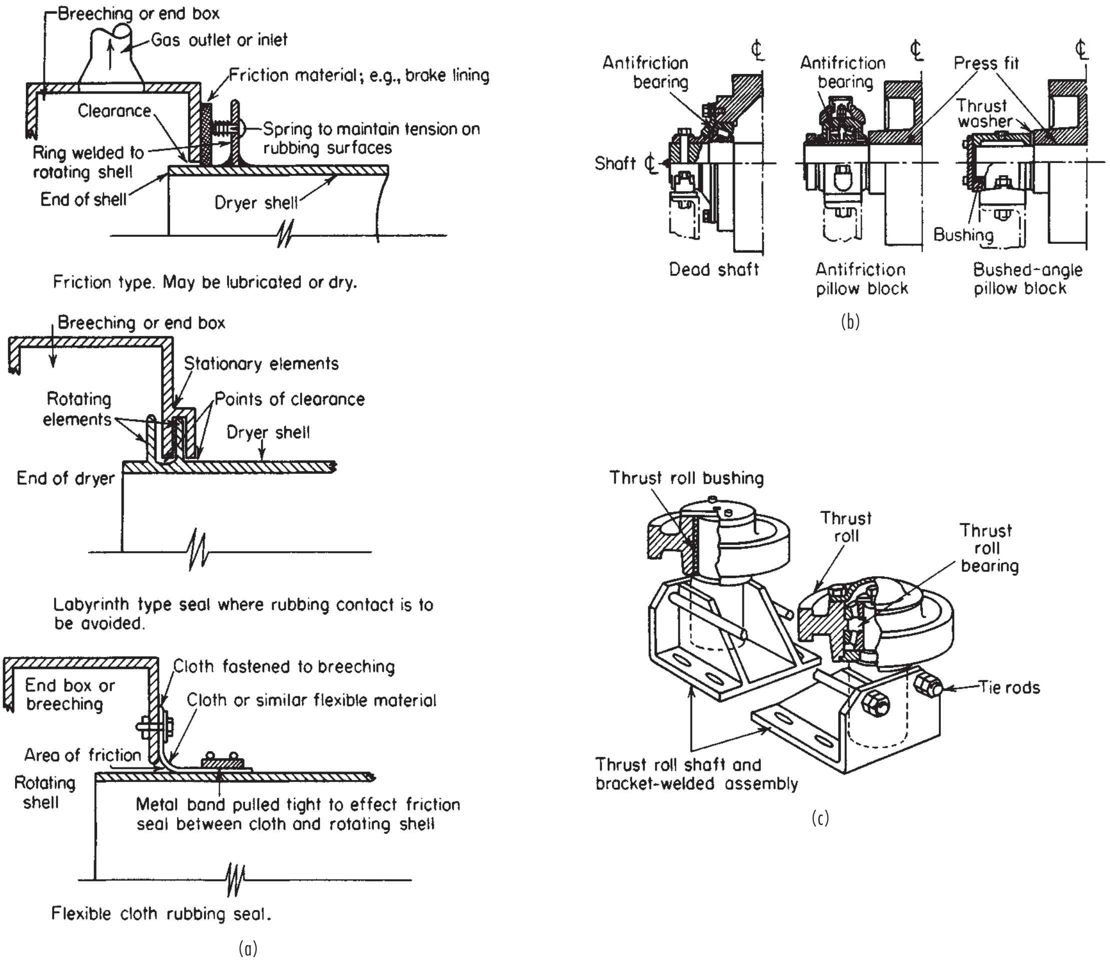


FIG. 12-61 Rotary-dryer components. (*a*) Alternative rotary gas seals. (*b*) Alternative trunnion roll bearings. (*c*) Thrust roll assembly. (*ABB Raymond/Bartlett-Snow TM.*)

Rotary dryers usually operate with 10 to 15 percent of *their volume filled with material.* Lower fillage will be insufficient to utilize the lifters fully, while greater fillage creates the possibility of short-circuiting feed solids across the top of the bed. Under normal fillage conditions, the dryer usually can be made to hold solids long enough to complete the removal of *internal moisture.* If the holdup in the dryer is not great enough, the time of passage may be too short to remove all internal moisture, or because of incomplete flight fillage performance may be erratic. The effect of fillage on retention time and uniformity in rotary dryers has been studied by Miskell and Marshall [*Chem. Eng. Prog.*, **52,** 1 (1956)].

Time of passage is defined as holdup divided by feed rate. It can be measured directly in rotary dryers if holdup and feed rate can be measured directly. Holdup cannot always be measured conveniently on large plant dryers, however, unless a period of shutdown occurs when the dryer can be discharged and its contents weighed. Other methods have been resorted to, one of which consists of adding a pound or two of an inert detectable solid or a radioisotope of a feed constituent to the feed and analyzing for it in the discharged product. The time required for the maximum concentration to occur represents the average time of passage.

The time of passage in rotary dryers can be estimated by the relationships developed by Friedman and Marshall (op. cit.), as given here:

$$\theta = \frac{0.23L}{SN^{0.9}D} \pm 0.6\,\frac{BLG}{F} \qquad (12\text{-}55)$$

$$B = 5(D_p)^{-0.5} \qquad (12\text{-}56)$$

where B = a constant depending upon the material being handled and approximately defined by Eq. (12-56); D_p = weight average particle size of material being handled, μm; F = feed rate to dryer, lb dry material/(h·ft^2 of dryer cross section); θ = time of passage, min; S = slope, ft/ft; N = speed, r/min; L = dryer length, ft; G = air-mass velocity, lb/(h·ft^2); and D = dryer diameter, ft. The plus sign refers to countercurrent flow and the negative sign to cocurrent flow. To convert from British thermal units per hour to watts, multiply by 0.293; to convert from pounds per hour-square foot of cross section to kilograms per second-square meter, multiply by 0.00135.

Air-mass velocities in rotary dryers usually range from 0.5 to 5.0 kg/(s·m^2). It is customary to employ the highest air velocity possible without serious dusting. The amount of dusting occurring during operation is a complex function of the material being dried, its physical state, the air velocity employed, the holdup in the dryer, the number of flights, the rate of rotation, and the construction of the breeching at the end of the dryer. It can be predicted accurately only by experimental tests. An air rate of 1.4 kg/(s·m^2) can usually be safely used with 35-mesh solids. Information on the dusting of a number of

TABLE 12-18 Warm-Air Direct-Heat Cocurrent Rotary Dryers: Typical Performance Data*

Dryer size, m × m	1.219 × 7.62	1.372 × 7.621	1.524 × 9.144	1.839 × 10.668	2.134 × 12.192	2.438 × 13.716	3.048 × 16.767
Evaporation, kg/h	136.1	181.4	226.8	317.5	408.2	544.3	861.8
Work, 10^8 J/h	3.61	4.60	5.70	8.23	1.12	1.46	2.28
Steam, kg/h at kg/m^2 gauge	317.5	408.2	521.6	725.7	997.9	131.5	2041
Discharge, kg/h	408	522	685	953	1270	1633	2586
Exhaust velocity, m/min	70	70	70	70	70	70	70
Exhaust volume, m^3/min	63.7	80.7	100.5	144.4	196.8	257.7	399.3
Exhaust fan, kW	3.7	3.7	5.6	7.5	11.2	18.6	22.4
Dryer drive, kW	2.2	5.6	5.6	7.5	14.9	18.6	37.3
Shipping weight, kg	7700	10,900	14,500	19,100	35,800	39,900	59,900
Price, FOB Chicago	$158,000	$168,466	$173,066	$204,400	$241,066	$298,933	$393,333

*Courtesy of Swenson Process Equipment Inc.

NOTE:
Material: heat-sensitive solid
Maximum solids temperature: 65°C
Feed conditions: 25 percent moisture, 27°C
Product conditions: 0.5 percent moisture, 65°C
Inlet-air temperature: 165°C
Exit-air temperature: 71°C
Assumed pressure drop in system: 200 mm.
System includes finned air heaters, transition piece, dryer, drive, product collector, duct, and fan.
Prices are for carbon steel construction and include entire dryer system (November, 1994).
For 304 stainless-steel fabrication, multiply the prices given by 1.5.

materials in a 0.3- by 2-m rotary dryer has been presented by Friedman and Marshall (ibid.). Rotary dryers operate at peripheral speeds of 0.25 to 0.5 m/s. Slopes of rotary-dryer shells vary from 0 to 8 cm/m. In some cases of cocurrent-flow operations, negative slopes have been used. The radial flight heights in a direct dryer will range from one-twelfth to one-eighth of the dryer diameter. The number of flights will range from 0.6 D to D, where D = diameter, m, for dryers larger than 0.6 m in diameter, and should be designed to carry and shower all the holdup and minimize any kiln action.

Performance and Cost Data for Direct-Heat Rotary Dryers Table 12-18 gives estimating-price data for direct rotary dryers employing steam-heated air. Higher-temperature operations requiring combustion chambers and fuel burners will cost more. The total installed cost of rotary dryers including instrumentation, auxiliaries, allocated building space, etc., will run from 150 to 300 percent of the purchase cost. Simple erection costs average 10 to 20 percent of the purchase cost.

Operating costs will include 5 to 10 percent of one worker's time, plus power and fuel required. Yearly maintenance costs will range from 50 to 10 percent of total installed costs. Total power for fans, dryer drive, and feed and product conveyors will be in the range of 0.5 D^2 to 1.0 D^2. Thermal efficiency of a high-temperature direct-heat rotary dryer will range from 55 to 75 percent and, with steam-heated air, from 30 to 55 percent.

A representative list of materials dried in direct-heat rotary dryers is given in Table 12-19.

Direct-Heat Rotary Kilns One of the most important of the high-temperature process furnaces is the direct-fired rotary kiln. It replaces the ordinary rotary dryer when the wall temperature exceeds that which can be tolerated by a bare metal shell (650 to 700 K for carbon steel). Rotary-kiln shells are lined in part or for their entire length with a **refractory brick** to prevent overheating of the steel with resulting weakening. Occasionally two linings are used, the one next to the shell being an **insulating brick.** Insulation is infrequently used on the outside of the shell, and caution must be observed not to overheat the shell metal by this confinement. When wet feeds are applied to a kiln lining at the cold end, there may be leakage of liquid through the lining to the shell, which will cause trouble if the liquid is corrosive.

The feed is introduced into the upper end of the kiln by various methods, i.e., inclined chutes, overhung screw conveyors, slurry pipes, etc. Sometimes **ring dams** or chokes of a refractory material are installed within the kiln to build a deeper bed at one or more points, thus changing the flow pattern. The hot product is discharged from the lower end of the kiln into quench tanks, onto conveyors, or into cooling devices which may or may not recover its heat content. These cooling and heat-recovery devices include rotating inclined cylinders, inclined slow-moving grates, shaking grates, etc.

Some kilns have two or three diameters, part of the length being one diameter and the remainder being another diameter. It is claimed that this arrangement increases kiln capacity, decreases fuel consumption, and improves product quality. Two types of kilns are depicted in Fig. 12-62. An enlarged cross section near the discharge end (and hot-gas inlet) reduces the gas velocity and provides increased holdup for a "soaking" period at high temperature.

The first rotary kilns used in the United States were very small, 2 by 20 m. Sizes gradually increased and seemed to stop for a period at a maximum size of 4 by 150 m. A few much larger units have been installed for cement production.

Modern rotary-kiln shells are of all-welded construction. Riding rings are forged or cast steel; support rollers are forged or cast steel and, on rare occasions, tool steel. Main bearings are sleeve-type, normally bronze. Antifriction bearings are frequently used on very small kilns but never on large units. However, bearings on the pinion shafts are normally of the antifriction type.

Gearing is single helical or spur; gear lubrication usually is an automatic spray type. Single drives are used up to 150 kW. Kilns requiring more than 150 kW may be equipped with dual drives, i.e., two driving

TABLE 12-19 Representative Materials Dried in Direct-Heat Rotary Dryers*

Material dried	Moisture content, % (wet basis) Initial	Final	Heat efficiency, %
High-temperature:			
Sand	10	0.5	61
Stone	6	0.5	65
Fluorspar	6	0.5	59
Sodium chloride (vacuum salt)	3	0.04	70–80
Sodium sulfate	6	0.1	60
Ilmenite ore	6	0.2	60–65
Medium-temperature:			
Copperas	7	1 (moles)	55
Ammonium sulfate	3	0.10	50–60
Cellulose acetate	60	0.5	51
Sodium chloride (grainer salt)	25	0.06	35
Cast-iron borings	6	0.5	50–60
Styrene	5	0.1	45
Low-temperature:			
Oxalic acid	5	0.2	29
Vinyl resins	30	1	50–55
Ammonium nitrate prills	4	0.25	30–35
Urea prills	2	0.2	20–30
Urea crystals	3	0.1	50–55

*Taken from *Chem. Eng.*, June 19, 1967, p. 190, Table III.

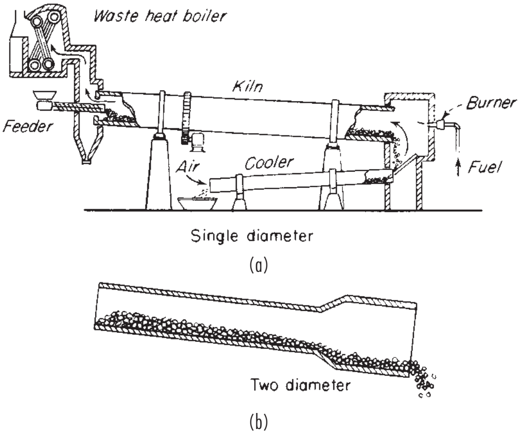


FIG. 12-62 Rotary kilns.

pinions and two motors, both driving one bull gear. In this manner, the power load is split through two separate driving mechanisms, meshing with one and the same gear.

Kiln inclination varies wtih processes from 2 to 6 cm/m. *Speed of rotation* also varies from very slow, i.e., a peripheral speed of 0.15 m/s for a TiO_2 pigment kiln, or 0.22 m/s for a cement kiln, to 0.64 m/s for a unit calcining phosphate materials.

Special features include the discharge end designed for air cooling or kilns that operate at high temperatures, such as cement, deadburned dolomite, and magnesia. Firing hoods are designed with retractable fronts and large side doors and are mounted on wheels. *Internal heat recuperators* are of numerous designs and are becoming more popular as fuel prices increase. *Thermocouple collector rings* are placed at various points on the shell for indicating and recording internal temperatures.

Scoop systems are provided for introducing collected dust or, in some cases, a feed component through the shell at some intermediate point or points. Ports are installed in the shell for admitting combustion air at points beyond the hot zone; these are used in reducing kilns for burning carbon monoxide and volatiles from materials being processed.

Firing may be accomplished at either end, depending on whether cocurrent or countercurrent flow of the charge and gases is desired. Sometimes a solid fuel is mixed with the charge and burned as it moves down the kiln. Gaseous, liquid, or powdered fuels may be used. The burner may be installed directly at the end of the kiln with combustion occurring inside it. In this case, the discharge-end housing usually consists of a fixed or movable kiln hood through which the fuel pipe enters the kiln. A center position for the fuel pipe is used when the flame is wanted off the charge. Some users prefer an off-center position toward the trough between the charge chord and the descending kiln lining. The kiln and the hood (combustion chamber) usually have open ends which coincide with each other with the gap being closed by a sliding seal (Fig. 12-63). Sometimes a special offset chamber for the introduction of secondary tempering air is provided on dryers and kilns (Fig. 12-64).

The exhaust gases are generally discharged into dust and fume knockdown equipment to avoid contamination of the atmosphere. Gas-cleaning equipment includes cyclones, settling chambers, scrubbing towers, and electrical precipitators. Heat-recovery devices are utilized both within and outside the kiln. These result in an increase in kiln capacity or a decrease in fuel consumption. Waste-heat boilers, grates, coil systems, and chains are used for this purpose.

The feed end of a rotary kiln is partially closed by a ring-shaped **feed head** which retains the end brick and dams back flow of solids. On the discharge end, a brick retaining-ring casting is made up to suit the application. For low temperatures, segmental alloy-iron rings may be employed. For high-temperature processes, either segmental alloy-steel rings or kiln ends of the air-cooled type are employed; the latter provides longer life for both kiln end and the brick ring.

Efficient **air seals** are essential for the controlled and economical operation of kilns. They reduce outside air entrance; certain types effectively prevent entrance of all outside air. The simplest type of air seal is a floating T-section ring mounted on a wearing pad around the feed end of the kiln and free to slide with expansion of the kiln shell. The web of the T ring is confined within circular retainer plates. Figure 12-65 shows two arrangements. The floating-type discharge-end air seal consists of a circular bar which floats on a wearing pad and which can be moved to provide the desired operating clearance between air seal and firing hood. The floating ring and the fixed portion of these seals can be furnished with renewable wearing surfaces. Air infiltration through this type of seal is usually less than 10 percent (Allis-Chalmers Corporation). For further reduction of air infiltration, lantern-ring-type floating seals, pressurized with inert gas or stack gases, are employed. Accelerated drying of slurries in the feed end of rotary kilns in wet-process operations is achieved by installation of *hanging chains.* Conveying spirals support suspended lengths of chain which are arranged in such a way that they form an effective pattern for drying. With the chain system, slurry is heated in three ways: by direct transfer from chains after suspension in hot gases, by lifting material into the path of hot gases, and by directing the flow of hot gas over the slurry bed in the space formed under the suspended chains. Frequently, the product forms into uniformly sized pellets which progress through the rest of the kiln in that form, resulting in improved heat transfer and reduced dust losses (Fig. 12-66).

Design Methods for Rotary Kilns In rotary kilns, the material is not showered through the air stream but is retained in the lower part of the cylinder. Gas-solids contacting is much less efficient than in flighted units. Heat transfer is by radiation and convection from the flowing gas to the kiln brick and exposed bed surface and by radiation from the brick to the bed. For units employing separate combustion chambers, it can be assumed that at high temperatures the wall-film

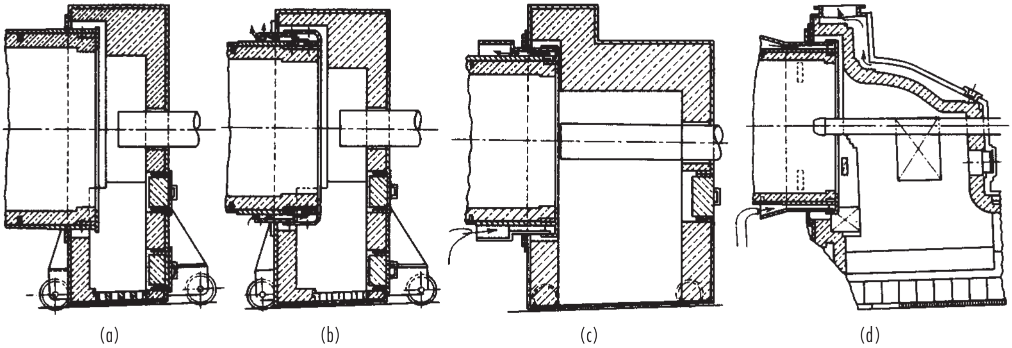


FIG. 12-63 Alternative kiln firing hoods. *(a)* Plain firing hood. *(b)* Hood for high temperatures. *(c)* Hood with enlarged combustion-air passage. *(d)* Hood with cooler connection. *(Allis-Chalmers Corporation.)*

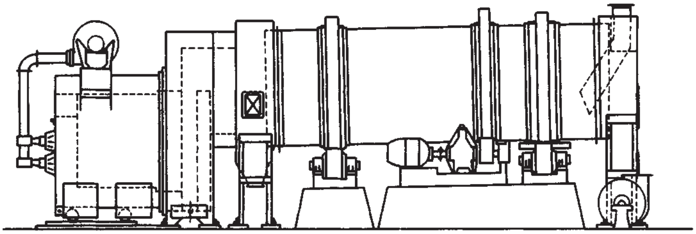


FIG. 12-64 Dryer firing hood with air-tempering chamber. *(ABB Raymond/Bartlett-Snow TM.)*

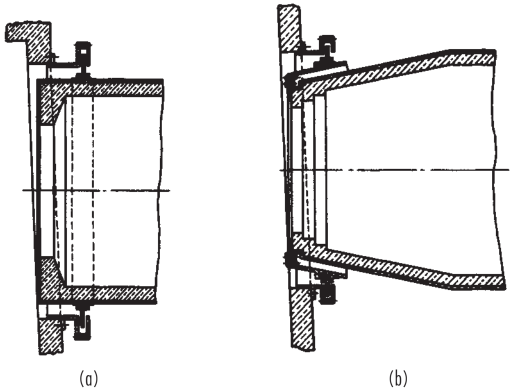


FIG. 12-65 Kiln-seal arrangements. *(a)* Single-floating-type feed end air seal. *(b)* Single-floating-type air seal on an air-cooled tapered feed end. *(Allis-Chalmers Corp.)*

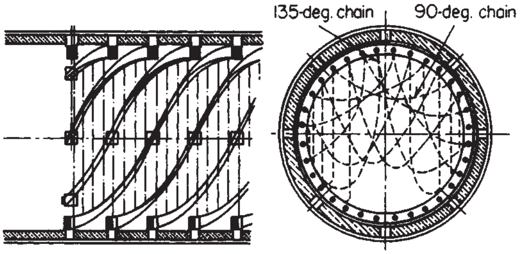


FIG. 12-66 Kiln chain installation (patented). *(Allis-Chalmers Corp.)*

resistance to convection heat transfer from the gas to the brick is limiting and that at any point the bed temperature approaches the wall temperature. Hence, the effective heat-transfer area is the inner kiln surface. For kilns under these conditions, the following empirical relationship is recommended for the convection heat-transfer coefficient from gas to brick:

$$Us = 23.7G^{0.67} \qquad (12\text{-}57)$$

where Us = heat-transfer coefficient, J/(m^2·s·K) [(Btu/(h·ft^2 kiln surface·°F)]; and G = gas mass flow rate, kg/(s·m^2 kiln cross section) [lb/(h·ft^2)].

Equation (12-57) does not account for gas radiation at high temperature when the kiln charge can "see" the burner flame; hence, the method will yield a conservative design. When a kiln is fired internally, the major source of heat transfer is radiation from the flame and hot gases. This occurs directly to both the solids surface and the wall, and from the latter to the product by reradiation (with some conduction).

Generally, a dry-feed kiln will have three zones of heating, and a wet-feed kiln will have four:

1. Drying zone at feed end, when moisture is removed
2. Heating zone, where the charge is heated to the reaction temperature, i.e., the decomposition temperature for limestone or "burning" temperature for cement
3. Reaction zone, in which the charge is burned, decomposed, reduced, oxidized, etc.
4. Soaking zone, where the reacted charge is superheated or "soaked" at temperature or, if desired, cooled before discharge

The rates of heat transfer in each zone will be different.

Rotary kilns operate at various temperatures throughout their length. A graph of approximate gas and charge temperatures for wet-process cement is shown in Fig. 12-67. The maximum charge temperature is 1700 to 1800 K; for the gases, 1800 to 1925 K. Overall heat-transfer rates have been estimated to be in the range of 25 to 60 KJ/(s·m^3) on the basis of total kiln volume.

Some commercial performance data for cement and lime kilns are shown in Table 12-20.

Some of the other major uses of direct rotary kilns are in the following processes:

Roasting. Rotary kilns are used for oxidizing and driving off sulfur and arsenic from various ores, including gold, silver, iron, etc. Temperatures employed will vary from 800 to 1600 K.

Chloridizing. Silver ores are chloridized successfully in rotary kilns. Temperatures must be closely controlled between 1030 and 1090 K.

Black ash. Barium sulfide (BaS) is produced by calcining a mixture of barite ($BaSO_4$) and carbon at a temperature of 1350 K in continuous rotary kilns.

Spodumene. A mixture of quartz, feldspar, and spodumene is being calcined in rotary kilns at 1475 K to produce lithium aluminum silicate.

Vermiculite. A micaceous mineral is roasted to cause exfoliation for use as an insulating material.

Revivification. Temperatures of 800 to 1030 K are used to revivify fuller's and diatomaceous earth, although for some earths lower temperatures are employed.

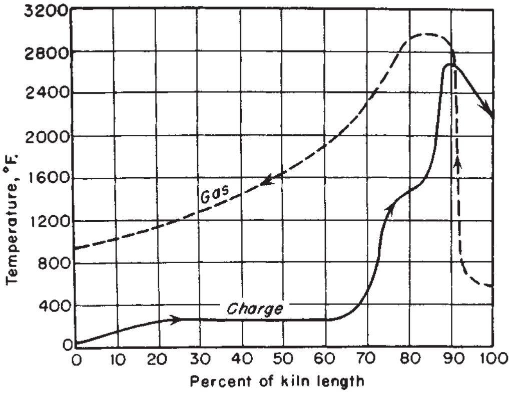


FIG. 12-67 Temperatures in rotary kiln on wet-process cement.

TABLE 12-20 Typical Rotary-Kiln Installations*

Size, diam. × length	Usual No. of supports	Range of motor hp. to operate†	Nominal 24-hr. capacities‡			
			Portland cement, 376-lb. bbl.		Lime, net tons	
			Dry process	Wet process	Lime sludge	Limestone
5 × 80 ft.	2	5–7.5	140	100	10	16
6 × 70 ft.	2	7.5–15	190	135	15	24
7 × 70 ft.	2	15–20	275	200	20	35
5 ft. 6 in. × 180 ft.	4	15–20	285	250	30	45
7 × 120 ft.	2	15–25	475	340	35	55
7 ft. 6 in. × 125 ft.	2	20–30	575	415	40	70
6 × 220 ft.	4	20–30	420	375	45	65
8 × 140 ft.	2	25–30	750	540	55	90
9 × 160 ft.	2	30–50	1100	800	80	130
8 ft. 6 in. × 185 ft.	4	30–50	1125	810	80	135
10 × 150 ft.	2	40–75	1300	950	—	145
10 × 175 ft.	2	50–75	1500	1100	—	155
8 × 300 ft.	5	50–75	1150	1000	110	160
7 ft. 6 in. × 8 ft. 6 in. × 320 ft.	5	50–75	1175	1020	115	165
7 ft. 6 in. × 10 ft. × 8 ft. 6 in. × 300 ft.	5	50–75	1175	1020		
10 × 11 × 175 ft.	2	50–75	1650	1200	120	180
10 ft. 6 in. × 185 ft.	2	50–75	1800	1300	130	190
11 × 175 ft.	2	60–100	1850	1375	—	205
8 ft. 6 in. × 10 ft. × 8 ft. 6 in. × 300 ft.	5	50–75	1400	1200		
8 × 10 × 300 ft.	5	50–75	1425	1225	140	200
9 ft. 6 in. × 265 ft.	4	60–100	1500	1300	150	215
9 × 10 ft. 6 in. × 9 ft. × 325 ft.	5	60–100	1700	1500		
10 ft. 6 in. × 250 ft.	4	60–100	1750	1525	175	240
9 ft. 6 in. × 11 ft. × 9 ft. 6 in. × 300 ft.	5	60–100	1800	1550		
10 × 300 ft.	5	75–125	1900	1650	190	250
9 ft. 6 in. × 11 ft. × 9 ft. 6 in. × 375 ft.	6	75–125	2025	1800		
11 × 300 ft.	5	75–125	2400	2100	225	300
11 ft. 6 in. × 300 ft.	4	100–150	2600	2250	240	320
10 ft. 6 in. × 375 ft.	5	100–150	2700	2400	250	325
11 ft. 3 in. × 360 ft.	5	125–175	2900	2500	275	350
11 ft. 6 in. × 475 ft.	7	150–250	4000	3500	375	450
12 × 500 ft.	8	200–300	4600	4000	425	500

*Allis-Chalmers Manufacturing Co.

†Power requirements vary according to size of kiln, character of material handled, and method of operation.

‡Capacities indicated are conservative, and apply to normal operation at sea level. Corrections would apply at increased altitudes, and for differing methods of operation.

Zinc. Oxidized ores are calcined to drive off water of hydration and carbon dioxide. The sulfide ore is always roasted before smelting.

Titanium oxide (TiO_2). This is produced from ilmenite ore by mixing ore with carbon and heating in a rotary kiln. Also, the rotary kiln is used in the process of recovery of titanium oxide from hydrated titanium precipitate at about 1250 K.

Roofing granules. Crushed quartz or sand of definite size is treated with various minerals, borax, soda ash, etc., and calcined at temperatures ranging from 1250 to 1600 K. Glass of different colors forms on the surface of the granules at various temperatures. An oxidizing or reducing flame is used to influence the final coloring.

Alumina (Al_2O_3). Alumina is produced by calcining either bauxite or aluminum hydroxide in rotary kilns at temperatures from 1250 to 1600 K. In obtaining the highest-purity alumina, the bauxite is digested with alkali to remove impurities; the resultant aluminum hydroxide [$Al_2(OH)_3$], of approximately 200-mesh size, is then calcined in rotary kilns at 1350 K.

Potassium salts. In this operation, potassium chloride (KCl) is introduced to the rotary kiln at a fineness of minus 100 mesh and containing 9 percent water. The salt is brought to the fusion temperature of 1048 K.

Magnesium oxide. The natural minerals, i.e., magnesite ($MgCO_3$), brucite [$Mg(OH)_2$], etc., after being crushed to predetermined size, are calcined at temperatures varying from 1055 to 2000 K, depending upon whether a caustic or a dead-burned product (periclase) is being produced. Magnesium hydroxide, recovered from seawater or salt brine, is also being treated in a similar manner except that it is added in the form of a sludge.

Sodium aluminum sulfate. This product is now being successfully calcined in rotary kilns. In this process, the salt cake is broken up just before it enters the kiln. Calcination is for the purpose of driving off the combined water (45 percent) and sulfuric acid (3 percent). Temperatures employed are approximately 800 K.

Phosphate rock. In this application, the rotary kiln is used to nodulize the fines in the ore and prepare them for electric-furnace operation. Ore under 5 cm in size and containing 50 percent or more minus 100 mesh is calcined. Ore nodulizes at approximately 1475 to 1500 K.

Mercury. In recovering mercury from cinnabar ores, the ore is crushed to minus 1.5 cm and fed to rotary kilns, where it is calcined to over 800 K. Since the mercury exists as mercuric sulfide (HgS), the sulfur is oxidized to SO_2 and the mercury vaporized. The gases are passed through cooling chambers, where the mercury condenses and is collected. Mercury vaporizes at 625 K.

Gypsum. The rotary kiln is rapidly replacing the kettle in producing plaster of paris. Great care is required, as the temperatures for reaction are low and within narrow limits, 382 to 403 K. Gypsum ($CaSO_4 \cdot 2H_2O$) is heated to drive off three-fourths of the water of crystallization to produce plaster of paris [$(CaSO_2) \cdot H_2O$]. Any overheating drives off all the water, producing gypsite ($CaSO_4$), which is unsatisfactory.

Clay. To produce lightweight aggregate for concrete, clay is calcined in rotary kilns. Temperatures employed vary from 1350 to 1600 K. The apparent density of the clay is reduced by 50 to 75 percent.

Iron ores. Crushed iron ores are partially reduced in rotary kilns to obtain nodules which are used in blast-furnace charges.

Manganese. Manganese ore, rhodochrosite, or manganese carbonate ($MnCO_2$) is calcined at about 1525 K to produce the oxide (Mn_3O_4). When the oxide ore is available but is in a finely divided state, the rotary kiln is used only for nodulizing.

Petroleum coke. In order to eliminate excess volatile matter, petroleum coke is calcined at temperatures of 1475 to 1525 K. This is a sensitive material, and temperature control is difficult to maintain.

When it is desired to increase the capacity of an existing kiln installation, consideration should be given to the following changes:

1. Increase charge volume held in kiln.
2. Increase temperature and quantity of combustion gases.
3. Decrease quantity of air in excess of combustion needs.
4. Increase speed of rotation of kiln.
5. Install ring dams at intermediate and discharge points.
6. Increase capacity of feeding and discharge mechanisms.
7. Decrease moisture content of feed material.
8. Increase temperature of feed material.
9. Install chains or flights, etc., in feed end.
10. Preheat all combustion air.
11. Reduce leakage of cold air into kiln at hot end.
12. Increase stack draft by increasing height or by use of jets.
13. Install instrumentation to control the kiln at maximum-capacity conditions.

The time of passage in rotary kilns (from which holdup can be calculated) can be estimated by the following formula (U.S. Bur. Mines Tech. Pap. 384, 1927):

$$\theta = 0.19L/NDS \tag{12-58}$$

where θ = time of passage in the kiln, min; L = kiln length, ft; N = rotational speed, r/min; S = slope of kiln, ft/ft; and D = diameter inside brick, ft. Other equations for estimating the time of passage employing internal dams and a discharge dam are given by Bayard [*Chem. Metall. Eng.*, **52**(3), 100–102 (1945)].

The total power required to drive a rotary kiln or a dryer with lifters can be calculated by the following formulas (courtesy of ABB Raymond). For a rotary kiln or calciner without lifters,

$$\text{bhp} = \frac{N\,[18.85y\,(\sin B)w + 0.1925DW + 0.33W]}{100{,}000} \tag{12-59}$$

For a rotary dryer or section of a kiln with lifters,

$$\text{bhp} = \frac{N\,(4.75dw + 0.1925DW + 0.33W)}{100{,}000} \tag{12-60}$$

where bhp = brake horsepower required (1 bhp = 0.75 kW); N = rotational speed, r/min; y = distance between centerline of kiln and the center of gravity of material bed, ft; B = angle of repose of material; W = total rotating load (equipment plus material), lb; w = live load (material), lb; D = riding-ring diameter, ft; and d = shell diameter, ft. For estimating purposes, let $D = (d + 2)$.

Drive motors should be of the high-starting-torque type and selected for 1.33 times maximum rotational speed. For two- or three-diameter kilns, the brake horsepower for the several diameters should be calculated separately and summed. Auxiliary drives should be provided to maintain shell rotation in the event of power failure. These are usually gasoline or diesel engines.

Thermal Efficiency of Rotary Kilns Kiln length is a major factor in determining thermal efficiency, and kilns with a high ratio of length to diameter have a greater thermal efficiency than those with a low ratio. The use of chains inside the kiln and of heat-recovery equipment on the gases and product leaving the kiln can increase substantially the thermal efficiency of a kiln installation. Efficiencies ranging from 45 to more than 80 percent have been reported. A reasonably satisfactory range based on present fuel prices and construction costs would be 65 to 75 percent utilization and recovery of the heat content of the fuel plus any heat of reaction of the charge. No distinction is made from an efficiency-calculation standpoint between the heat utilized in the kiln and that recovered (or utilized) outside the kiln. With countercurrent flow of the combustion gases and the charge material, an exceptionally long kiln will give high efficiencies within itself. However, good economics may dictate that a shorter kiln be installed with a waste-heat boiler on the hot gases to obtain an equivalent thermal efficiency at a lower investment. The heat in the hot product usually is recovered as preheat in the combustion air.

Size Segregation in Kilns When an assemblage of solid particles, not very closely screened, is rotated within a cylinder, the solids assume a lunar shape, as shown in Fig. 12-68. This causes serious size segregation. The finest sizes remain at the bottom, in contact with the hot brick. The coarser particles form the upper layer of the agitated mass. As the kiln completes a revolution, the exposed brick, in an upper position, absorbs sensible heat from the gas mass. As the heated brick completes its circuit, it passes under and is in conductive contact with the fine particles. These fines are thus effectively heated by direct solid-to-solid transfer. The larger particles are heated by direct radiation from gas and brick, and become adequately calcined. The particles of size intermediate between the fine and coarse remain, throughout a complete revolution, "sandwiched" between the coarse and fine layers and are protected from heat by the excellent insulation properties of these layers, thus perhaps escaping complete calcination. This factor of segregation is offset by some kiln operators who classify or screen the kiln feed so that only a narrow range of particle size is fed at one time. Also, faster kiln speeds which give a better agitation of the charge are used.

Rotary kilns are usually operated with between 3 and 12 percent of their volume filled with material; 7 percent is considered normal.

Cost Data for Kilns Purchase prices, weights, and horsepower requirements of typical units are given in Table 12-21. Installed costs will run to from 300 to 500 percent of purchase cost. Maintenance will average 5 to 10 percent of the total installed cost per year but is dependent largely on the life of the refractory lining.

For estimating purposes refractory lining for a 2.7- to 3.4-m-diameter kiln costs $6000 to $15,000 per meter of kiln length installed (50 percent material, 50 percent labor).

A discussion of retention time in rotary kilns is given in *Brit. Chem. Eng.*, 27–29 (January 1966). Rotary-kiln heat control is discussed in detail by Bauer [*Chem. Eng.*, 193–200 (May 1954)] and Zubrzycki [*Chem. Can.*, 33–37 (February 1957)]. Reduction of iron ore in rotary kilns is described by Stewart [*Min. Congr. J.*, 34–38 (December 1958)]. The use of balls to improve solids flow is discussed in [*Chem. Eng.*, 120–222 (March 1956)]. Brisbane examined problems of shell deformation [(*Min. Eng.*, 210–212 (February 1956)]. Instrumentation is discussed by Dixon [*Ind. Eng. Chem. Process Des. Dev.*, 1436–1441 (July 1954)], and a mathematical simulation of a rotary kiln was developed by Sass [*Ind. Eng. Chem. Process Des. Dev.*, 532–535 (October 1967)]. This last paper employed the empirical convection heat-transfer coefficient given previously, and its use is discussed in later correspondence [ibid., 318–319 (April 1968)].

Indirect-Heat Rotary Steam-Tube Dryers Probably the most common type of indirect-heat rotary dryer is the steam-tube dryer (Fig. 12-69). Steam-heated tubes running the full length of the cylinder are fastened symmetrically in one, two, or three concentric rows inside the cylinder and rotate with it. Tubes may be simple pipe with condensate draining by gravity into the discharge manifold or bayonet-type. Bayonet-type tubes are also employed when units are used

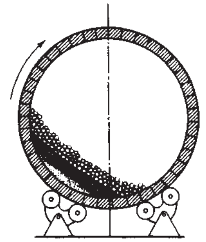


FIG. 12-68 Size segregation of solids in a rotary kiln.

TABLE 12-21 Approximate Purchase Costs and Weight of Rotary Kilns*

Kiln size, diameter × length	Total purchase price includes drive, burner, and controls (not including brick)†
8′0″ × 80′0″	$ 448,000
8′0″ × 140′0″	600,000
8′0″ × 200′0″	960,000
8′0″ × 300′0″	1,240,000
9′0″ × 250′0″	1,373,000
9′0″ × 300′0″	1,545,000
10′0″ × 100′0″	682,000
10′0″ × 150′0″	965,000
10′0″ × 250′0″	1,502,000
10′0″ × 300′0″	1,682,000
10′0″ × 350′0″	1,779,000
10′6″ × 175′0″	1,182,000
10′6″ × 250′0″	1,677,000
10′6″ × 350′0″	1,942,000
11′0″ × 160′0″	1,213,000
11′0″ × 250′0″	1,670,000
11′0″ × 300′0″	1,858,000
11′0″ × 350′0″	2,344,000
11′0″ × 400′0″	2,544,000
11′6″ × 160′0″	1,251,000
11′6″ × 250′0″	1,768,000
11′6″ × 350′0″	2,393,000
11′6″ × 425′0″	2,676,000
12′0″ × 250′0″	1,837,000
12′0″ × 325′0″	2,598,000
12′0″ × 400′0″	2,645,000
12′0″ × 450′0″	3,570,000
13′0″ × 500′0″	4,388,000
14′0″ × 400′0″	4,155,000
16′6″ × 600′0″	8,190,000

*Courtesy of Fuller Co.
†Prices for January 1982

as water-tube coolers. When handling sticky materials, one row of tubes is preferred. These are occasionally shielded at the feed end of the dryer to prevent buildup of solids behind them. Lifting flights are usually inserted behind the tubes to promote solids agitation.

Wet feed enters the dryer through a chute or screw feeder. The product discharges through peripheral openings in the shell in ordinary dryers. These openings also serve to admit purge air to sweep moisture or other evolved gases from the shell. In practically all cases, gas flow is countercurrent to solids flow. To retain a deep bed of material within the dryer, normally 10 to 20 percent fillage, the discharge openings are supplied with removable chutes extending radially into the dryer. These, on removal, permit complete emptying of the dryer.

Steam is admitted to the tubes through a revolving steam joint into the steam side of the manifold (Fig. 12-70). Condensate is removed continuously, by gravity through the steam joint to a condensate receiver and my means of lifters in the condensate side of the manifold. By employing simple tubes, noncondensables are continuously vented at the other ends of the tubes through Sarco-type vent valves mounted on an auxiliary manifold ring, also revolving with the cylinder.

Vapors (from drying) are removed at the feed end of the dryer to the atmosphere through a natural-draft stack and settling chamber or wet scrubber. When employed in simple drying operations with 3.5×10^5 to 10×10^5 Pa steam, draft is controlled by a damper to admit only sufficient outside air to sweep moisture from the cylinder, discharging the air at 340 to 365 K and 80 to 90 percent saturation. In this way, shell gas velocities and dusting are minimized. When used for solvent recovery or other processes requiring a sealed system, sweep gas is recirculated through a scrubber-gas cooler and blower.

Steam manifolds for pressures up to 10×10^5 Pa are of cast iron. For higher pressures, the manifold is fabricated from plate steel, staybolted, and welded. The tubes are fastened rigidly to the manifold face plate and are supported in a close-fitting annular plate at the other end to permit expansion. Packing on the steam neck is normally graphite-asbestos. Ordinary rotating seals are similar in design to those depicted in Fig. 12-61, with allowance for the admission of small quantities of outside air when the dryer is operated under a slight negative internal pressure.

Steam-tube dryers are used for the continuous drying, heating, or cooling of granular or powdery solids which cannot be exposed to ordinary atmospheric or combustion gases. They are especially suitable for fine dusty particles because of the low gas velocities required for purging of the cylinder. Tube sticking is avoided or reduced by employing recycle, shell knockers, etc., as previously described; tube scaling by sticky solids is one of the major hazards to efficient operation. The dryers are suitable for drying, solvent recovery, and chemical reactions. Steam-tube units have found effective employment in

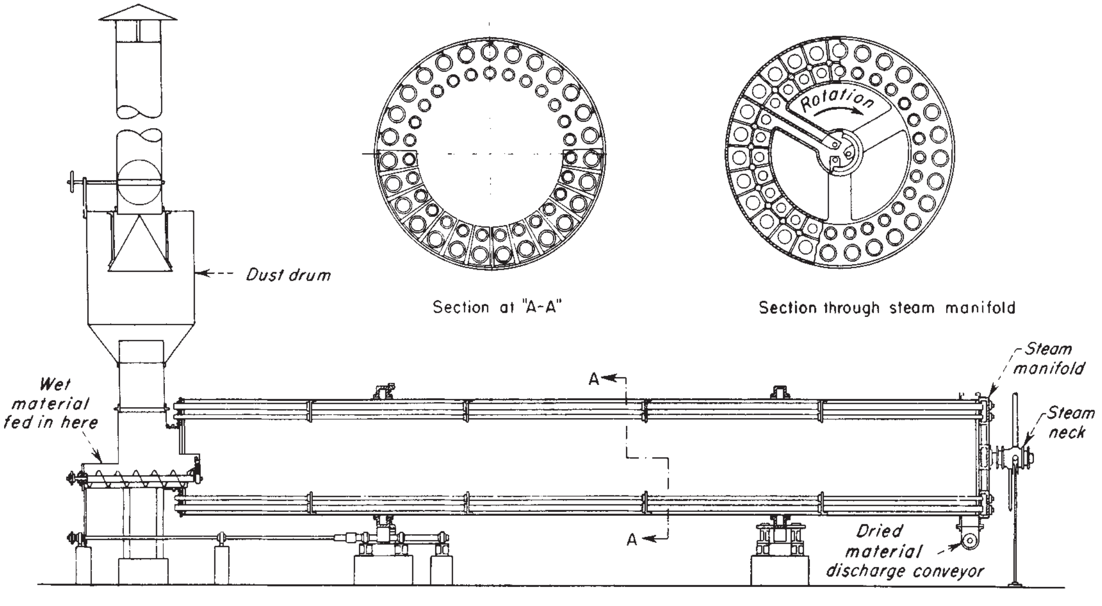


FIG. 12-69 Steam-tube rotary dryer.

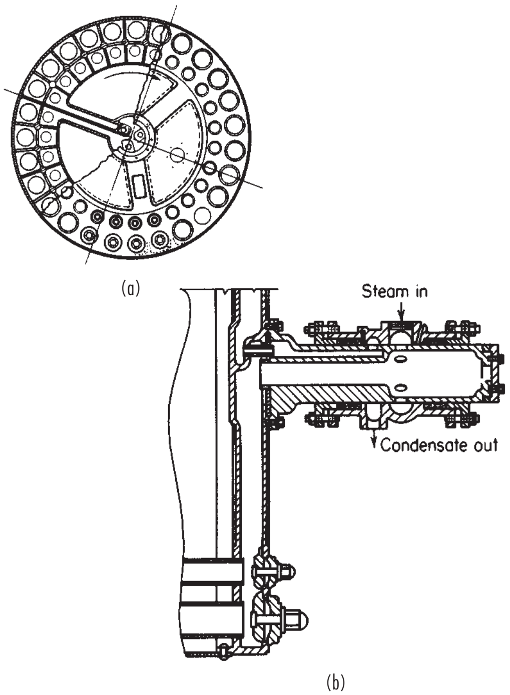


FIG. 12-70 Rotary steam joint for a standard steam-tube dryer. *(a)* Section of cast-steam manifold. *(b)* Section of manifold and steam joint.

soda-ash production, replacing more expensive indirect-heat rotary calciners.

Special types of steam-tube dryers employ packed and purged seals on all rotating joints, with a central solids-discharge manifold through the steam neck to reduce the seal diameter. This manifold contains the product discharge conveyor and a passage for the admission of sweep gas. Solids are removed from the shell by special volute lifters and dropped into the discharge conveyor. Units have been fabricated for operation at 76 mm of water, internal shell pressure, with no detectable air leakage.

Design Methods for Indirect-Heat Rotary Steam-Tube Dryers Heat-transfer coefficients in steam-tube dryers range from 30 to 85 J/($m^2 \cdot s \cdot K$). Coefficients will increase with increasing steam temperature because of increased heat transfer by radiation. In units carrying saturated steam at 420 to 450 K, the heat flux $U\Delta T$ will range from 6300 J/($m^2 \cdot s$) for difficult-to-dry and organic solids and to 1890 to 3790 J/($m^2 \cdot s$) for finely divided inorganic materials. The effect of steam pressure on heat-transfer rates up to 8.6×10^5 Pa is illustrated in Fig. 12-71.

Performance and Cost Data for Indirect-Heat Rotary Steam-Tube Dryers Table 12-22 contains data for a number of standard sizes of steam-tube dryers. Prices tabulated are for ordinary carbon steel construction. Installed costs will run from 150 to 300 percent of purchase cost.

The thermal efficiency of steam-tube units will range from 70 to 90 percent, if a well-insulated cylinder is assumed. This does not allow for boiler efficiency, however, and is therefore not directly comparable with direct-heat units such as the direct-heat rotary dryer or indirect-heat calciner.

Operating costs for these dryers include 5 to 10 percent of one person's time. Maintenance will average 5 to 10 percent of total installed cost per year.

Table 12-23 outlines typical performance data from three drying applications in steam-tube dryers.

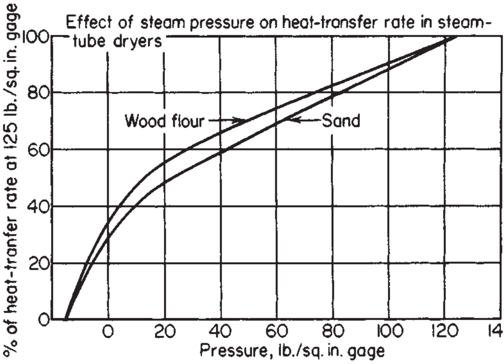


FIG. 12-71 Effect of steam pressure on the heat-transfer rate in steam-tube dryers.

Indirect-Heat Calciners Indirect-heat rotary calciners, either batch or continuous, are employed for heat treating and drying at higher temperatures than can be obtained in steam-heated rotating equipment. They generally require a minimum flow of gas to purge the cylinder, to reduce dusting and are suitable for gas-sealed operation with oxidizing, inert, or reducing atmospheres. Indirect calciners are widely utilized and some examples of specific applications are as follows:

1. Activating charcoal
2. Reducing mineral high oxides to low oxides
3. Drying and devolatilizing contaminated soils and sludges
4. Calcination of alumina oxide-based catalysts
5. Drying and removal of sulfur from cobalt, copper, and nickel
6. Reduction of metal oxides in a hydrogen atmosphere
7. Oxidizing and "burning off" of organic impurities
8. Calcination of ferrites

This unit consists essentially of a cylindrical retort, rotating within a stationary insulation lined furnace. The latter is arranged so that fuel combustion occurs within the annular ring between the retort and the furnace. The retort cylinder extends beyond both ends of the furnace. These end extensions carry the riding rings and drive gear. Material may be fed continuously at one end and discharged continuously at the other. Feeding and solids discharging are usually accomplished with screw feeders or other positive feeders to prevent leakage of gases into or out of the calciner.

In some cases in which it is desirable to cool the product before removal to the outside atmosphere, the discharge end of the cylinder is provided with an additional extension, the exterior of which is water-spray-cooled. In cocurrent-flow calciners, hot gases from the interior of the heated portion of the cylinder are withdrawn through a special extraction tube. This tube extends centrally through the cooled section to prevent flow of gas near the cooled-shell surfaces and possible condensation. Frequently a separate cooler is used, isolated from the calciner by an air lock.

To prevent sliding of solids over the smooth interior of the shell, agitating flights running longitudinally along the inside wall are frequently provided. These normally do not shower the solids as in a direct-heat vessel but merely prevent sliding so that the bed will turn over and constantly expose new surface for heat and mass transfer. To prevent scaling of the shell interior by sticky solids, cylinder scraper and knocker arrangements are occasionally employed. For example, a scraper chain is fairly common practice in soda-ash calciners, while knockers are frequently utilized on metallic-oxide calciners.

Because indirect-heat calciners frequently require close-fitting gas seals, it is customary to support all parts on a self-contained frame, for sizes up to approximately 2 m in diameter. The furnace can employ electric heating elements or oil and/or gas burners as the heat source for the process. The hardware would be zoned down the length of the furnace to match the heat requirements of the process. Process control is normally by shell temperature, measured by thermocouples or radiation pyrometers. When a special gas atmosphere must be maintained inside the cylinder, positive rotary gas seals, with one or more pressurized and purged annular chambers, are employed. The diaphragm-type seal ABB Raymond (Bartlett-Snow TM) is suitable for pressures up to 5 cm of water, with no detectable leakage.

TABLE 12-22 Standard Steam-Tube Dryers*

Size, diameter × length, m	Tubes		m² of free area	Dryer speed, r/min	Motor size, hp	Shipping weight, kg	Estimated price
	No. OD (mm)	No. OD (mm)					
0.965 × 4.572	14 (114)		21.4	6	2.2	5,500	$152,400
0.965 × 6.096	14 (114)		29.3	6	2.2	5,900	165,100
0.965 × 7.620	14 (114)		36.7	6	3.7	6,500	175,260
0.965 × 9.144	14 (114)		44.6	6	3.7	6,900	184,150
0.965 × 10.668	14 (114)		52.0	6	3.7	7,500	196,850
1.372 × 6.096	18 (114)	18 (63.5)	58.1	4.4	3.7	10,200	203,200
1.372 × 7.620	18 (114)	18 (63.5)	73.4	4.4	3.7	11,100	215,900
1.372 × 9.144	18 (114)	18 (63.5)	88.7	5	5.6	12,100	228,600
1.372 × 10.668	18 (114)	18 (63.5)	104	5	5.6	13,100	243,840
1.372 × 12.192	18 (114)	18 (63.5)	119	5	5.6	14,200	260,350
1.372 × 13.716	18 (114)	18 (63.5)	135	5.5	7.5	15,000	273,050
1.829 × 7.62	27 (114)	27 (76.2)	118	4	5.6	19,300	241,300
1.829 × 9.144	27 (114)	27 (76.2)	143	4	5.6	20,600	254,000
1.829 × 10.668	27 (114)	27 (76.2)	167	4	7.5	22,100	266,700
1.829 × 12.192	27 (114)	27 (76.2)	192	4	7.5	23,800	278,400
1.829 × 13.716	27 (114)	27 (76.2)	217	4	11.2	25,700	292,100
1.829 × 15.240	27 (114)	27 (76.2)	242	4	11.2	27,500	304,800
1.829 × 16.764	27 (114)	27 (76.2)	266	4	14.9	29,300	317,500
1.829 × 18.288	27 (114)	27 (76.2)	291	4	14.9	30,700	330,200
2.438 × 12.192	90 (114)		394	3	11.2	49,900	546,100
2.438 × 15.240	90 (114)		492	3	14.9	56,300	647,700
2.438 × 18.288	90 (114)		590	3	14.9	63,500	736,600
2.438 × 21.336	90 (114)		689	3	22.4	69,900	838,200
2.438 × 24.387	90 (114)		786	3	29.8	75,300	927,100

*Courtesy of Swenson Process Equipment Inc. (prices from November, 1994). Carbon steel fabrication; multiply by 1.75 for 304 stainless steel.

TABLE 12-23 Steam-Tube Dryer Performance Data

	Class 1	Class 2	Class 3
Class of materials handled	High-moisture organic, distillers' grains, brewers' grains, citrus pulp	Pigment filter cakes, blanc fixe, barium carbonate, precipitated chalk	Finely divided inorganic solids, water-ground mica, water-ground silica, flotation concentrates
Description of class	Wet feed is granular and damp but not sticky or muddy and dries to granular meal	Wet feed is pasty, muddy, or sloppy; product is mostly hard pellets	Wet feed is crumbly and friable; product is powder with very few lumps
Normal moisture content of wet feed, % dry basis	233	100	54
Normal moisture content of product, % dry basis	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 product, kg	2	1	0.53
Heat load per lb product, kJ	2250	1190	625
Steam pressure normally used, kPa gauge	860	860	860
Heating surface required per kg product, m²	0.34	0.4	0.072
Steam consumption per kg product, kg	3.33	1.72	0.85

In general, the temperature range of operation for indirect-heated calciners can vary over a wide range, from 475 K at the low end to approximately 1475 K at the high end. All types of carbon steel, stainless, and alloy construction are used, depending upon temperature, process, and corrosion requirements. Fabricated-alloy cylinders can be used over the greater part of the temperature range; however, the greater creep-stress abilities of cast alloys makes their use desirable for the highest calciner-cylinder temperature applications.

Design Methods for Calciners In indirect-heated calciners, heat transfer is primarily by radiation from the cylinder wall to the solids bed. The thermal efficiency ranges from 30 to 65 percent. By utilization of the furnace exhaust gases for preheated combustion air, steam production, or heat for other process steps, the thermal efficiency can be increased considerably. The limiting factors in heat transmission lie in the conductivity and radiation constants of the shell metal and solids bed. If the characteristics of these are known, equipment may be accurately sized by employing the Stefan-Boltzmann radiation equation. Apparent heat-transfer coefficients will range from 17 J/(m²·s·K) in low-temperature operations to 85 J/(m²·s·K) in high-temperature processes.

Cost Data for Calciners Power, operating, and maintenance costs are similar to those previously outlined for direct- and indirect-heat rotary dryers. Estimating purchase costs for preassembled and frame-mounted rotary calciners with carbon steel and type 316 stainless-steel cylinders are given in Table 12-24 together with size, weight, and motor requirements. Sale price includes the cylinder, ordinary angle seals, furnace, drive, feed conveyor, burners, and controls. Installed cost may be estimated, not including building or foundation costs at up to 50 percent of the purchase cost. A layout of a typical continuous calciner with an extended cooler section is illustrated in Fig. 12-72.

Small batch retorts, heated electrically or by combustion, are widely used as carburizing furnaces and are applicable also to chemical processes involving the heat treating of particulate solids. These are mounted on a structural-steel base, complete with cylinder, furnace, drive motor, burner, etc. Units are commercially available in diameters from 0.24 to 1.25 m and lengths of 1 to 2 m. Continuous retorts with helical internal spirals are employed for metal-heat-treating purposes. Precise retention control is maintained in these operations. Standard diameters are 0.33, 0.5, and 0.67 m with effective lengths up

TABLE 12-24 Indirect-Heat Rotary Calciners: Sizes and Purchase Costs*

Diameter, ft	Overall cylinder length	Heated cylinder length	Cylinder drive motor hp	Approximate Shipping weight, lb	Approximate sale price in carbon steel construction†	Approximate sale price in No. 316 stainless construction
4	40 ft	30 ft	7.5	50,000	$275,000	$325,000
5	45 ft	35 ft	10	60,000	375,000	425,000
6	50 ft	40 ft	20	75,000	475,000	550,000
7	60 ft	50 ft	30	90,000	550,000	675,000

* ABB Raymond (Bartlett-Snow™).
† Prices for November, 1994.

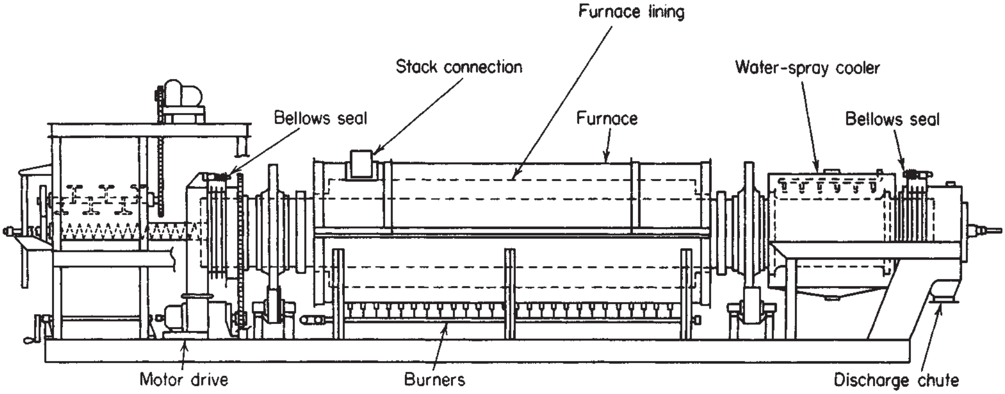


FIG. 12-72 Gas-fired indirect-heat rotary calciner with a water-spray extended cooler and feeder assembly. (*ABB Raymond/ Bartlett-Snow™*.)

to 3 m. These vessels are employed in many small-scale chemical-process operations which require accurate control of retention. Their operating characteristics and applications are identical to those of the larger indirect-heat calciners.

Direct-Heat Roto-Louvre Dryer One of the more important special types of rotating equipment is the Roto-Louvre dryer. As illustrated in Fig. 12-73, hot air (or cooling air) is blown through louvers in a double-wall rotating cylinder and up through the bed of solids. The latter moves continuously through the cylinder as it rotates. Constant turnover of the bed ensures uniform gas contacting for heat and mass transfer. The annular gas passage behind the louvers is partitioned so that contacting air enters the cylinder only beneath the solids bed. The number of louvers covered at any one time is roughly 30 percent. Because air circulates through the bed, fillages of 13 to 15 percent or greater are employed.

Roto-Louvre dryers range in size from 0.8 to 3.6 m in diameter and from 2.5 to 11 m long. The largest unit is reported capable of evaporating 5500 kg/h of water. Hot gases from 400 to 865 K may be employed. Because gas flow is through the bed of solids, high pressure drop, from 7 to 50 cm of water, may be encountered within the shell. For this reason, both a pressure inlet fan and an exhaust fan are provided in most applications to maintain the static pressure within the equipment as closely as possible to atmospheric. This prevents excessive in-leakage or blowing of hot gas and dust to the outside. For pressure control, one fan is usually operated under fixed conditions, with an automatic damper control on the other, regulated by a pressure detector-controller.

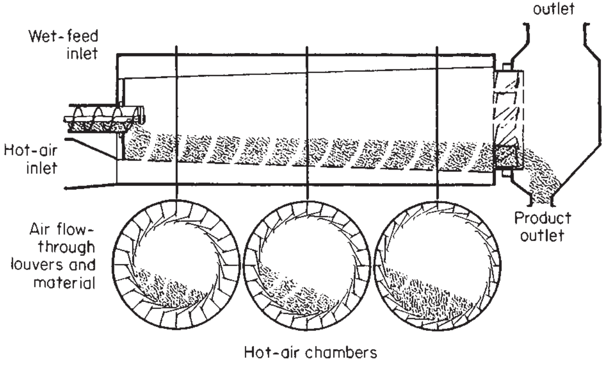


FIG. 12-73 Link-Belt Roto-Louvre dryer. (*Material Handling Systems Division, FMC Corp.*)

In heating or drying applications, when cooling of the product is desired before discharge to the atmosphere, cool air is blown through a second annular space, outside the inlet hot-air annulus, and released through the louvers at the solids-discharge end of the shell.

Roto-Louvre dryers are suitable for processing coarse granular solids which do not offer high resistance to air flow, require intimate gas contacting, and do not contain significant quantities of dust.

Heat and mass transfer from the gas to the surface of the solids is extremely efficient; hence the equipment size required for a given duty is frequently less than required when an ordinary direct-heat rotary vessel with lifting flights is used. Purchase-price savings are partially balanced, however, by the more complex construction of the Roto-Louvre unit. A Roto-Louvre dryer will have a capacity roughly 1.5 times that of a single-shell rotary dryer of the same size under equivalent operating conditions. Because of the cross-flow method of heat exchange, the average Δt is not a simple function of inlet and outlet Δt's. There are currently no published data which permit the sizing of equipment without pilot tests as recommended by the manufacturer. Three applications of Roto-Louvre dryers are outlined in Table 12-25. Installation, operating, power, and maintenance costs will be similar to those experienced with ordinary direct-heat rotary dryers. *Thermal efficiency* will range from 30 to 70 percent.

AGITATED DRYERS

Description An agitated dryer is defined as one on which the housing enclosing the process is stationary while solids movement is accomplished by an internal mechanical agitator. Many forms are in use, including batch and continuous versions.

Field of Application Agitated dryers are applicable to process-

TABLE 12-25 Manufacturer's Performance Data for FMC Link-Belt Roto-Louvre Dryers*

Material dried	Ammonium sulfate	Foundry sand	Metallurgical coke
Dryer diameter	2 ft 7 in	6 ft 4 in	10 ft 3 in
Dryer length	10 ft	24 ft	30 ft
Moisture in feed, % wet basis	2.0	6.0	18.0
Moisture in product, % wet basis	0.1	0.5	0.5
Production rate, lb/h	2500	32,000	38,000
Evaporation rate, lb/h	50	2130	8110
Type of fuel	Steam	Gas	Oil
Fuel consumption	255 lb/h	4630 ft^3/h	115 gal/h
Calorific value of fuel	837 Btu/lb	1000 Btu/ft^3	150,000 Btu/gal
Efficiency, Btu, supplied per lb evaporation	4370	2170	2135
Total power required, hp	4	41	78

*Material Handling Systems Division, FMC Corp. To convert British thermal units to kilojoules, multiply by 1.06; to convert horsepower to kilowatts, multiply by 0.746.

ing solids which are relatively free-flowing and granular when discharged as product. Materials which are not free-flowing in their feed condition can be treated by recycle methods as described in the subsection "Rotary Dryers." In general, agitated dryers have applications similar to those of rotating vessels. Their chief advantages compared with the latter lie in the fact that (1) large-diameter rotary seals are not required at the solids and gas feed and exit points because the housing is stationary, and for this reason gas-leakage problems are minimized. Rotary seals are required only at the points of entrance of the mechanical agitator shaft. (2) Use of a mechanical agitator for solids mixing introduces shear forces which are helpful for breaking up lumps and agglomerates. Balling and pelleting of sticky solids, an occasional occurrence in rotating vessels, can be prevented by special agitator design. The problems concerning dusting of fine particles in direct-heat units are identical to those discussed under "Rotary Dryers."

Batch Vacuum Rotary Dryers The more common type of vacuum rotary dryer 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. Heat is supplied by circulation of hot water, steam, or Dowtherm through a jacket surrounding the shell and, in larger units, through the hollow central shaft. The agitator is either 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.

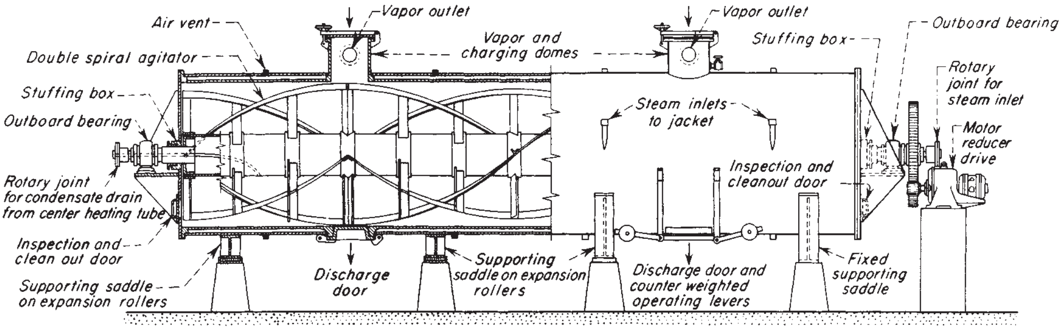
Another type of vacuum rotary dryer consists of a rotating horizontal cylindrical shell, suitably jacketed. Vacuum is applied to this unit through hollow trunnions with suitable packing glands. Rotary glands must be used also for admitting and removing the heating medium from the jacket. The inside of the shell may have lifting bars, welded longitudinally, to assist agitation of the solids.

The double-cone rotating vacuum dryer is a more common design. Although it is identical in operating design, the sloping walls of the cones permit more rapid emptying of solids when the dryer is in a stationary position. The older cylinder shape required continuous rotation during emptying to convey product to the discharge nozzles. As a result, a circular dust hood was frequently necessary to enclose the discharge-nozzle turning circle and prevent serious dust losses to the atmosphere during unloading. Several new designs of the double-cone type employ internal tubes or plate coils to provide additional heating surface.

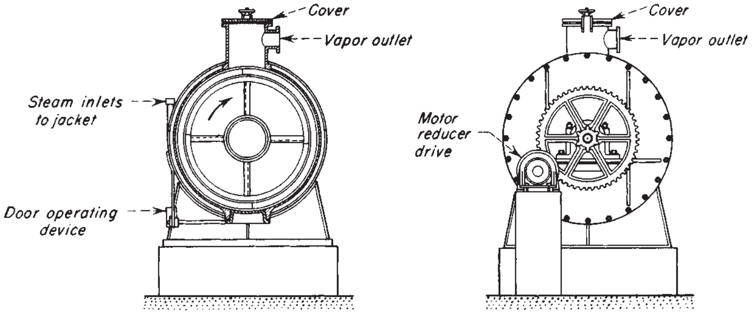
On all rotating dryers, the vapor-outlet tube is stationary; it enters the shell through a rotating gland and is fitted with an elbow and an upward extension so that the vapor inlet, usually protected by a felt dust filter, will be at all times near the top of the shell.

A typical vacuum rotary dryer is illustrated in Fig. 12-74 and a double-cone vacuum dryer in Fig. 12-75.

Vacuum is used in conjunction with drying or other chemical oper-



Elevation and partial cross section



Cross sectional view

Drive end view

FIG. 12-74 A typical vacuum dryer. (*Blaw-Knox Food & Chemical Equipment, Inc.*)

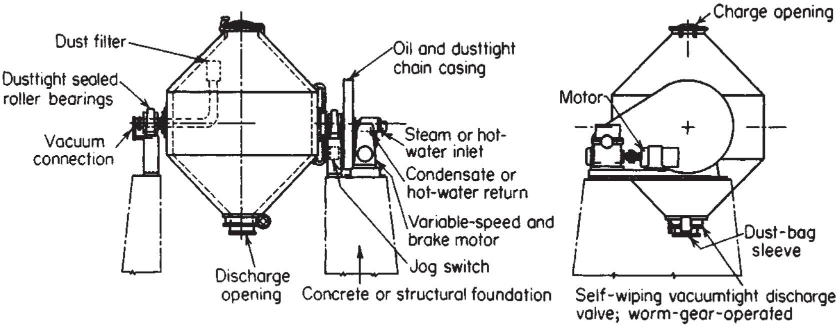


FIG. 12-75 Rotating (double-cone) vacuum dryer. (*Stokes Vacuum, Inc.*)

ations when low solids temperatures must be maintained because heat will cause damage to the product or change its nature, when air combines with the product as it is heated, causing oxidation or an explosive condition, when solvent recovery is required, and when materials must be dried to extremely low moisture levels.

In vacuum processing and drying the objective is to create a large temperature-driving force between the jacket and the product. To accomplish this purpose at fairly low jacket temperatures, it is necessary to reduce the internal process pressure so that the liquid being removed will boil at a lower vapor pressure. It is not always economical, however, 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.

Design Methods for Batch Vacuum Rotary Dryers The rate of heat transfer from the heating medium through the dryer wall to the solids can be expressed by

$$Q = UA\Delta t_m \qquad (12\text{-}61)$$

where Q = heat flux, J/s (Btu/h); U = overall heat-transfer coefficient, J/(m^2·s·K) [Btu/(h·ft^2 jacket area·°F)]; A = total jacket area, m^2; and Δt_m = log-mean-temperature driving force from heating medium to the solids, K.

The overall heat-transfer rate is almost entirely dependent upon the film coefficient between the inner jacket wall and the solids, which depends to a large extent on the solids characteristics. Overall coefficients may range from 30 to 200 J/(m^2·s·K), based upon total area if the dryer walls are kept reasonably clean. Coefficients as low as 5 or 10 may be encountered if caking on the walls occurs.

For estimating purposes without tests, a reasonable coefficient for ordinary drying, and without taking the product to absolute dryness, may be assumed at U = 50 J/(m^2·s·K) for rotary agitator dryers and 35 J/(m^2·s·K) for rotating units.

Vacuum dryers are usually filled to 50 to 65 percent of their total shell volume. Agitator speeds range from 3 to 8 r/min. Faster speeds yield a slight improvement in heat transfer but consume more power.

Performance and Cost Data for Batch Vacuum Rotary Dryers Typical performance data for vacuum rotary dryers are given in Table 12-26. Size and cost data for rotary agitator units are given in Table 12-27. Data for double-cone units are in Table 12-28.

Turbo-Tray Dryers The turbo-tray dryer is a continuous dryer consisting of a stack of rotating annular shelves in the center of which turbo-type fans revolve to circulate the air over the shelves. Wet material enters through the roof, falling onto the top shelf as it rotates beneath the feed opening. After completing one revolution, the mate-

TABLE 12-26 Performance Data of Vacuum Rotary Dryers*

Material	Diameter × length, m	Initial moisture, % dry basis	Steam pressure, Pa × 10^3	Agitator speed, r/min	Batch dry weight, kg	Final moisture, % dry basis	Pa × 10^3	Time, h	Evaporation, kg/(h·m^2)
Cellulose acetate	1.5 × 9.1	87.5	97	5.25	610	6	90–91	7	1.5
Starch	1.5 × 9.1	45–48	103	4	3630	12	88–91	4.75	7.3
Sulfur black	1.5 × 9.1	50	207	4	3180	1	91	6	4.4
Fuller's earth/mineral spirit	0.9 × 3.0	50	345	6	450	2	95	8	5.4

*Stokes Vacuum, Inc.

TABLE 12-27 Standard Rotary Vacuum Dryers*

Diameter, m	Length, m	Heating surface, m^2	Working capacity, m^3†	Agitator speed, r/min	Drive, kW	Weight, kg	Purchase price (1995)	
							Carbon steel	Stainless steel (304)
0.46	0.49	0.836	0.028	7½	1.12	540	$ 43,000	$ 53,000
0.61	1.8	3.72	0.283	7½	1.12	1,680	105,000	130,000
0.91	3.0	10.2	0.991	6	3.73	3,860	145,000	180,000
0.91	4.6	15.3	1.42	6	3.73	5,530	180,000	205,000
1.2	6.1	29.2	3.57	6	7.46	11,340	270,000	380,000
1.5	7.6	48.1	6.94	6	18.7	15,880	305,000	440,000
1.5	9.1	57.7	8.33	6	22.4	19,050	330,000	465,000

*Stokes Vacuum, Inc. Prices include shell, 50-lb/in^2-gauge jacket, agitator, drive, and motor; auxiliary dust collectors, condensers.
†Loading with product level on or around the agitator shaft.

TABLE 12-28 Standard (Double-Cone) Rotating Vacuum Dryers*

Working capacity, m^3	Total volume, m^3	Heating surface, m^2	Drive, kW	Floor space, m^2	Weight, kg	Purchase cost (1995)	
						Carbon steel	Stainless steel
0.085	0.130	1.11	.373	2.60	730	$ 32,400	$ 38,000
0.283	0.436	2.79	.560	2.97	910	37,800	43,000
0.708	1.09	5.30	1.49	5.57	1810	50,400	57,000
1.42	2.18	8.45	3.73	7.15	2040	97,200	106,000
2.83	4.36	13.9	7.46	13.9	3860	198,000	216,000
4.25	6.51	17.5	11.2	14.9	5440	225,000	243,000
7.08	10.5	*38.7	11.2	15.8	9070	324,000	351,000
9.20	13.9	*46.7	11.2	20.4	9980	358,000	387,000
11.3	16.0	*56.0	11.2	26.0	10,890	378,000	441,000

*Stokes Vacuum, Inc. Price includes dryer, 15-lb/in^2 jacket, drive with motor, internal filter, and trunnion supports for concrete or steel foundations. Horsepower is established on 65 percent volume loading of material with a bulk density of 50 lb/ft^3. Models of 250 ft^3, 325 ft^3, and 400 ft^3 have extended surface area.

rial is wiped by a stationary wiper through radial slots onto the shelf below, where it is spread into a uniform pile by a stationary leveler. The action is repeated on each shelf, with transfers occurring once in each revolution. From the last shelf, material is discharged through the bottom of the dryer (Fig. 12-76). The steel-frame housing consists of removable insulated panels for access to the interior. All bearings and lubricated parts are exterior to the unit with the drives located under the housing. Parts in contact with the product may be of steel or special alloy. The trays can be of any sheet material, such as enameled steel, asbestos-cement composition board, or plastic-glass laminates.

The rate at which each fan circulates air can be varied by changing the pitch of the fan blades. In final drying stages, in which diffusion controls or the product is light and powdery, the circulation rate is considerably lower than in the initial stage, in which high evaporation rates prevail. In the majority of applications, air flows through the dryer upward in counterflow to the material. In special cases, required drying conditions dictate that air flow be cocurrent or both countercurrent and cocurrent with the exhaust leaving at some level between solids inlet and discharge. A separate cold-air-supply fan is provided if the product is to be cooled before being discharged.

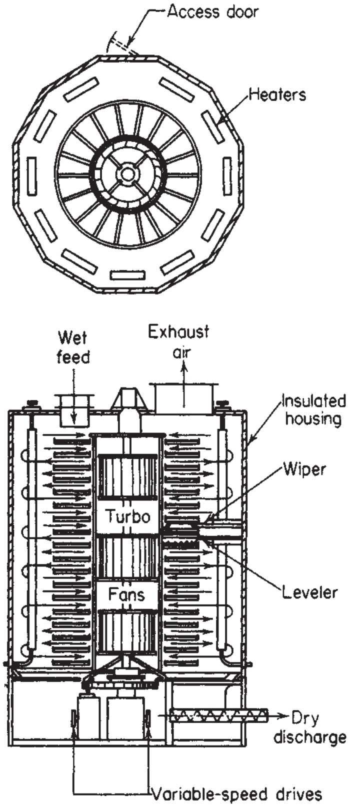


FIG. 12-76 Turbo-tray dryer. (*Wyssmont Company, Inc.*)

By virtue of its vertical construction, the turbo-type tray dryer has a stack effect, the resulting draft being frequently sufficient to operate the dryer with natural draft. Pressure at all points within the dryer is maintained close to atmospheric, as low as 0.1, usually less than 0.5 mm of water. Most of the roof area is used as a breeching, lowering the exhaust velocity to settle dust back into the dryer.

Heaters can be located in the space between the trays and the dryer housing, where they are not in direct contact with the product, and thermal efficiencies up to 3500 kJ/kg (1500 Btu/lb) of water evaporated can be obtained by reheating the air within the dryer. Steam is the usual heating medium. The high cost of heating electrically generally restricts its use to relatively small equipment. For materials which have a tendency to foul internal heating surfaces, an external heating system is employed.

The turbo-tray dryer can handle materials from thick slurries [1 million (N·s)/m^2 (100,000 cP) and over] to fine powders. It is not suitable for fibrous materials which mat or for doughy or tacky materials. Thin slurries can often be handled by recycle of dry product. Filter-press cakes are granulated before feeding. Thixotropic materials are fed directly from a rotary filter by scoring the cake as it leaves the drum. Pastes can be extruded onto the top shelf and subjected to a hot blast of air to make them firm and free-flowing after one revolution.

The turbo-tray dryer is manufactured in sizes from package units 2 m in height and 1.5 m in diameter to large outdoor installations 20 m in height and 11 m in diameter. Tray areas range from 1 for laboratory dryers to 1675 m^2 for large-scale production in a single unit. The number of shelves in a tray rotor varies according to space available and minimum rate of transfer required, from as few as 12 shelves to as many as 58 in the largest units. Standard construction permits operating temperatures up to 615 K, and high-temperature heaters permit operation at temperatures up to 925 K.

A recent innovation has enabled TURBO-Dryers to operate with very low inert gas make-up. Wyssmont has designed a tank housing that is welded up around the internal structure rather than the column-and-gasket panel design that has been the Wyssmont standard for many years. In field-erected units, the customer does the welding in the field; in packaged units, the tank-type welding is done in the shop. The tank-type housing finds particular application for operation under positive pressure. On the standard design, doors with explosion latches and gang latch operators are used. In the tank-type design, tight-sealing manway-type openings permit access to the interior. Tank-type housing designs have been requested when drying solvent wet materials and for applications where the material being dried is highly toxic and certainty is required that no toxic dust get out.

Design Methods for Turbo-Tray Dryers The heat- and mass-transfer mechanisms are similar to those in batch tray dryers, except that constant turning over and mixing of the solids significantly improves drying rates. Design must usually be based on previous installations or pilot tests by the manufacturer; apparent heat-transfer

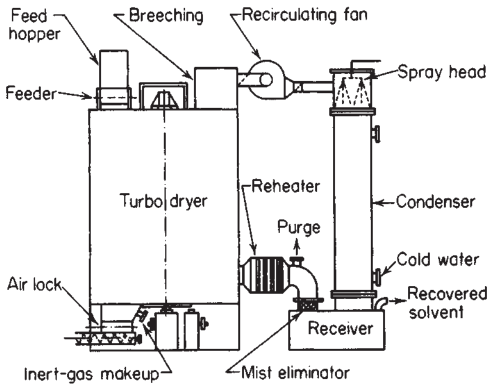


FIG. 12-77 Turbo-tray dryer in closed circuit for continuous drying with solvent recovery. (*Wyssmont Company, Inc.*)

coefficients will range from 28 to 55 J/(m²·s·K) for dry solids to 68 to 115 J/(m²·s·K) for wet solids. Turbo-tray dryers have been employed successfully for the drying and cooling of calcium hypochlorite, urea crystals, calcium chloride flakes, and sodium chloride crystals. The Wyssmont "closed-circuit" system, as shown in Fig. 12-77, consists of the turbo-tray dryer with or without internal heaters, recirculation fan, condenser with receiver and mist eliminators, and reheater. Feed and discharge are through a sealed wet feeder and lock respectively. This method is used for continuous drying without leakage of fumes, vapors, or dust to the atmosphere. A unified approach for scaling up dryers such as turbo-tray, plate, conveyor, or any other dryer type that forms a defined layer of solids next to a heating source is described by C. G. Moyers [*Drying Technology—An International Journal,* **12**(1 and 2), 393 (1994)].

Performance and Cost Data for Turbo-Tray Dryers Performance data for three applications of closed-circuit drying are included in Table 12-29. Operating, labor, and maintenance costs compare favorably with those of direct-heat rotating equipment.

Plate Dryers The plate dryer is an indirect-heated, fully continuous dryer available for three modes of operation: atmospheric, gastight, or full vacuum. The dryer is of vertical design, with horizontal, heated plates mounted inside the housing. The plates are heated by either hot water, steam, or thermal oil, with operating temperatures up to 320°C possible. The product enters at the top and is conveyed through the dryer by a product-transport system consisting of a central-rotating shaft with arms and plows. (See dryer schematic, Fig. 12-78.) The thin product layer (approx. ½ in depth) on the surface of the plates, coupled with frequent product turnover by the conveying system, results in short-retention times (approx. 5–40 min), true plug flow of the material, and uniform drying. The vapors are removed from the dryer by a small amount of heated purge gas or by vacuum. The material of construction of the plates and housing is normally stainless steel, with special metallurgies also available. The drive unit is located at the bottom of the dryer and supports the central-rotating shaft. Typical speed of the dryer is 1–7 rpm. Full-opening doors are located on two adjacent sides of the dryer for easy access to dryer internals.

The plate dryer may vary in size from 5–35 vertically stacked plates with a heat-exchange area between 3.8–175 m². The largest unit available has overall dimensions of 3 m (w) by 4 m (l) by 10 m (h). Depending upon the loose-bulk density of the material and the overall retention time, the plate dryer can process up to 5,000 kg/hr of wet product.

The plate dryer is limited in its scope of applications only in the consistency of the feed material (the products must be friable, free flowing, and not undergo phase changes) and drying temperatures up to 320°C. Applications include specialty chemicals, pharmaceuticals, foods, polymers, pigments, etc. Initial moisture or volatile level can be as high as 65 percent and the unit is often used as a final dryer to take materials to a bone-dry state, if necessary. The plate dryer can also be used for heat treatment, removal of waters of hydration (bound moisture), solvent removal, and as a product cooler.

The atmospheric plate dryer is a dust-tight system. The dryer housing is an octagonal, panel construction, with operating pressure in the range of ±0.5 kPa gauge. An exhaust-air fan draws the purge air through the housing for removal of the vapors from the drying process. The purge-air velocity through the dryer is in the range of 0.1–0.15 m/sec, resulting in minimal dusting and small dust filters for the exhaust air. The air temperature is normally equal to the plate temperature. The vapor laden exhaust air is passed through a dust filter or a scrubber (if necessary) and is discharged to the atmosphere. Normally, water is the volatile to be removed in this type of system.

The gastight plate dryer, together with the components of the gas-recirculation system, forms a closed system. The dryer housing is semicylindrical and is rated for a nominal pressure of +5 kPa gauge. The flow rate of the recirculating purge gas must be sufficient to absorb the vapors generated from the drying process. The gas temperature must be adjusted according to the specific product characteristics and the type of volatile. After condensation of the volatiles, the purge gas (typically nitrogen) is recirculated back to the dryer via a blower and heat exchanger. Solvents such as methanol, toluene, and acetone are normally evaporated and recovered in the gastight system.

The vacuum plate dryer is provided as part of a closed system. The vacuum dryer has a cylindrical housing and is rated for full-vacuum operation (typical pressure range 3–27 kPa absolute). The exhaust vapor is evacuated by a vacuum pump and is passed through a condenser for solvent recovery. There is **no** purge-gas system required for operation under vacuum. Of special note in the vacuum-drying system

TABLE 12-29 Turbo-Tray Dryer Performance Data in Wyssmont Closed-Circuit Operations*

Material dried	Antioxidant	Water-soluble polymer	Antibiotic filter cake	Petroleum coke
Dried product, kg/h	500	85	2400	227
Volatiles composition	Methanol and water	Xylene and water	Alcohol and water	Methanol
Feed volatiles, % wet basis	10	20	30	30
Product volatiles, % wet basis	0.5	4.8	3.5	0.2
Evaporation rate, kg/h	53	16	910	302
Type of heating system	External	External	External	External
Heating medium	Steam	Steam	Steam	Steam
Drying medium	Inert gas	Inert gas	Inert gas	Inert gas
Heat consumption, J/kg	0.56×10^6	2.2×10^6	1.42×10^6	1.74×10^6
Power, dryer, kW	1.8	0.75	12.4	6.4
Power, recirculation fan, kW	5.6	5.6	37.5	15
Materials of construction	Stainless-steel interior	Stainless-steel interior	Stainless-steel interior	Carbon steel
Dryer height, m	4.4	3.2	7.6	6.5
Dryer diameter, m	2.9	1.8	6.0	4.5
Recovery system	Shell-and-tube condenser	Shell-and-tube condenser	Direct-contact condenser	Shell-and-tube condenser
Condenser cooling medium	Brine	Chilled water	Tower water	Chilled water
Location	Outdoor	Indoor	Indoor	Indoor
Approximate cost of dryer (1995)	$225,000	$115,000	$425,000	$225,000
Dryer assembly	Packaged unit	Packaged unit	Field-erected unit	Field-erected unit

*Courtesy of Wyssmont Company, Inc.

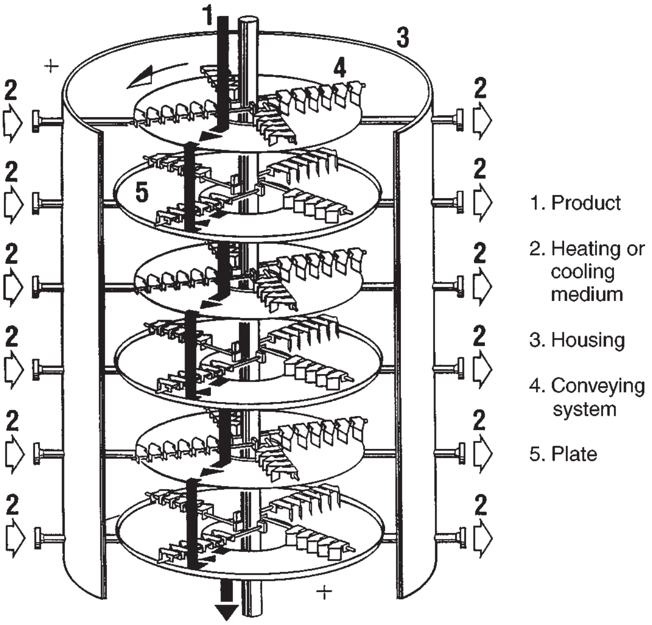


FIG. 12-78 Indirect-heated continuous plate dryer for atmospheric, gastight, or full-vacuum operation. (*Krauss Maffei.*)

are the vacuum feed and discharge locks, which allow for continuous operation of the plate dryer under full vacuum.

Comparison Data—Plate Dryers Comparative studies have been done on products under both atmospheric and vacuum drying conditions. See Fig. 12-79. These curves demonstrate (1) the improvement in drying achieved with elevated temperature and (2) the impact to the drying process obtained with vacuum operation. Note that curve 4 at 90°C, pressure at 6.7 kPa absolute, is comparable to the atmospheric curve at 150°C. Also, the comparative atmospheric curve at 90°C requires 90 percent more drying time than the vacuum condition. The dramatic improvement with the use of vacuum is important to note for heat-sensitive materials.

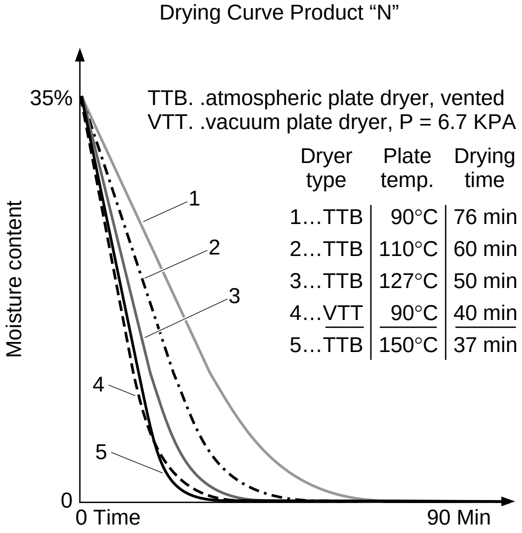


FIG. 12-79 Plate dryer drying curves demonstrating impact of elevated temperature and/or operation under vacuum. (*Krauss Maffei.*)

The above drying curves have been generated via testing on a plate-dryer simulator. The test unit duplicates the physical setup of the production dryer, therefore linear scale-up from the test data can be made to the full-scale dryer. Because of the thin product layer on each plate, drying in the unit closely follows the normal type of drying curve in which the constant-rate period (steady evolution of moisture or volatiles) is followed by the falling-rate period of the drying process. This results in higher heat-transfer coefficients and specific drying capacities on the upper plates of the dryer as compared to the lower plates. The average specific drying capacity for the plate dryer is in the range of 2–20 $kg/m^2 \cdot hr$ (based on final dry product). Performance data for typical applications are shown on Table 12-30.

Conical Mixer Dryer The conical mixer dryer is a batch-wise operating unit commonly used in the pharmaceutical and specialty chemical industries for the drying of solvent or water wet, free-flowing powders. The process area is a vertically oriented conical vessel with an internally mounted screw. Figure 12-80 shows a schematic of the bottom drive conical mixer dryer. The dryer utilizes the heatable, internal rotating screw to provide agitation of the batch of material and thus improve the heat and mass transfer of the process. Because it rotates around the full circumference of the vessel, the screw provides a self-cleaning effect for the heated vessel walls.

The distinguishing feature of this dryer is the bottom-screw drive, as opposed to a top-drive unit, thus eliminating any mechanical drive components inside the vessel. The bottom-driven screw rotates about its own axis (speeds up to 100 rpm) and around the interior of the vessel (speeds up to 0.4 rpm). The screw is cantilevered in the vessel and requires no additional support (even in vessel sizes up to 20 m^3 operating volume). The dryer is available in a variety of materials of construction, including SS 304 and 316, as well as Hastelloy.

The heatable areas of the dryer are the vessel wall and the screw. 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. 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. In addition to the conical vessel heated area, heating the screw effectively increases the heat exchange area by 15–30 percent. This is accomplished via rotary joints at the base of the screw. The screw can be heated with the same

TABLE 12-30 Plate Dryer Performance Data for Three Applications*

Product	Plastic additive	Pigment	Foodstuff
Volatiles	Methanol	Water	Water
Production rate, dry	362 kg/hr	133 kg/hr	2030 kg/hr
Inlet volatiles content	30%	25%	4%
Final volatiles content	0.1%	0.5%	0.7%
Evaporative rate	155 kg/hr	44 kg/hr	70 kg/hr
Heating medium	Hot water	Steam	Hot water
Drying temperature	70°C	150°C	90°C
Dryer pressure	11 kPa abs	atmospheric	atmospheric
Air velocity	NA	0.1 m/sec	0.2 m/sec
Drying time, min	24	23	48
Heat consumption, kcal/kg dry product	350	480	100
Power, dryer drive	3 kW	1.5 kW	7.5 kW
Material of construction	SS 316L/316Ti	SS 316L/316Ti	SS 316L/316Ti
Dryer height	5 m	2.6 m	8.2 m
Dryer footprint	2.6 m diameter	2.2 m by 3.0 m	3.5 m by 4.5 m
Location	Outdoors	Indoors	Indoors
Dryer assembly	Fully assembled	Fully assembled	Fully assembled
Power, exhaust fan	NA	2.5 kW	15 kW
Power, vacuum pump	20 kW	NA	NA

*Krauss Maffei

medium as the conical jacket (either hot water, steam, or thermal oil). Obviously, the impact of the heated screw will mean shorter batch-drying times, which yields higher productivity and better product quality due to shorter exposure to the drying temperature.

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. A dust filter is normally mounted directly on the top head of the dryer, thus allowing any entrapped dust to be pulsed back into the process area. Standard cloth-type dust filters are available, along with sintered metal filters. Because there are no drive components in the process area, the risk of batch failures due to contamination from gear lubricants is eliminated. Cleaning of the conical mixer dryer is facilitated with CIP systems and/or the vessel can be

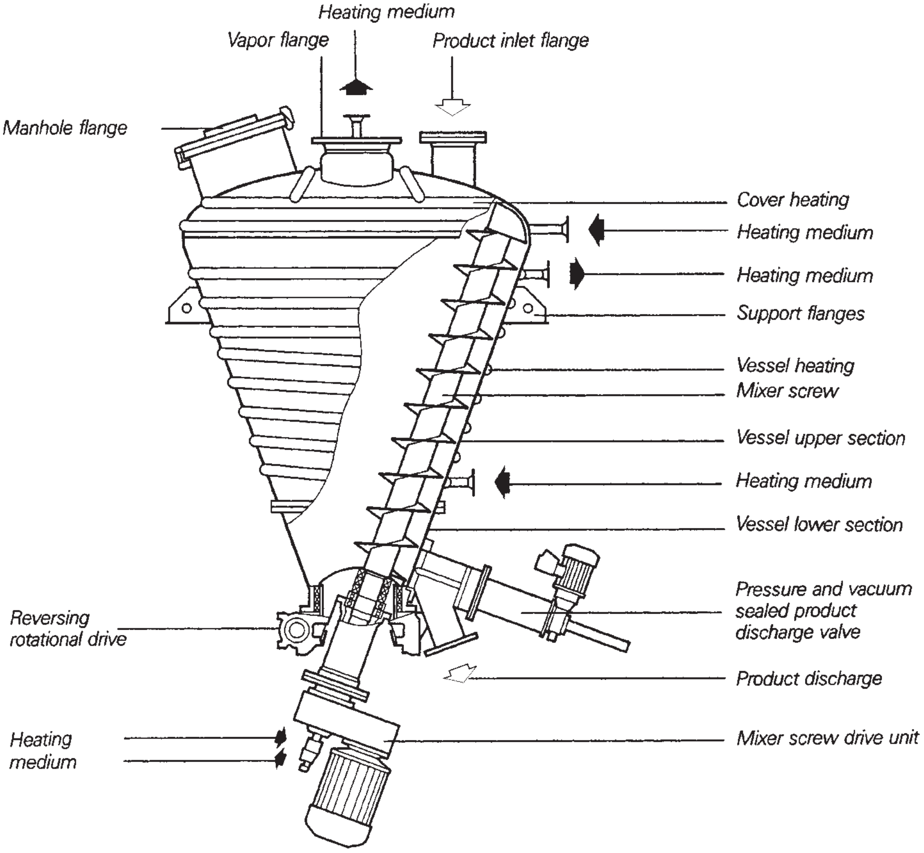


FIG. 12-80 Bottom drive conical mixer dryer. (*Krauss Maffei*.)

completely flooded with water or solvents. 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 removed from the bottom of the dryer.

Since the dryer is a batch-operating unit, it is commonly used in the pharmaceutical industry to maintain batch identification. In addition to pharmaceutical materials, the conical mixer dryer is used to dry polymers, additives, inorganic salts, and many other specialty chemicals.

The conical mixer dryer is an indirect (conduction) dryer designed to operate under full vacuum. The heating medium is either hot water, steam, or thermal oil, with most applications in the temperature range of 50–150°C and pressures in the range of 3–30 kPa absolute. The vapors generated during the drying process are evacuated by a vacuum pump and passed through a condenser for recovery of the solvent.

Design Methods for Conical Mixer Dryers Drying trials are conducted in small pilot dryers (50–100 liter batch units) to determine material handling and drying retention times. Variables such as drying temperature, vacuum level, and screw speed are analyzed during the test trials. Scale-up to larger units is done based upon the area to volume ratio of the pilot unit versus the production dryer. In most applications, the overall drying time in the production models is in the range of 2–24 hours. For design purposes, the heat-transfer coefficient for the conical mixer dryer is 60 $W/m^2 \cdot K$.

Reactotherm The reactotherm is a special thermal processor which has been designed to overcome the problems encountered with standard horizontal rotary-type dryers, such as crust formation on the heat-exchange surfaces and stalling of the rotor during drying. Incorporated in the design of the reactotherm is a high torque drive combined with rugged shaft construction to prevent rotor stall during processing; in addition, stationary mixing elements are installed in the process housing which continually clean the heat-exchange surfaces of the rotor to minimize any crust buildup and ensures an optimum heat-transfer coefficient at all times. Because the unit can handle a wide range of product consistencies (dilute slurries, pastes, friable powders) the reactotherm can be used for processes such as reactions, mixing, drying, cooling, melting, sublimation, distilling, and vaporizing.

The reactotherm is an indirect-heated thermal processor available in both batch and continuous design. Figure 12-81 shows a sketch of the continuous model. The unit is of horizontal design, with both the shell and internal rotor heated to provide high heat-transfer area/product volume ratio. The units are conduction dryers, with operation in atmospheric, pressure and vacuum mode possible. Sizes range from 170 up to 10,000 liter operating volume with heat-exchange area from 3.1 m^2 up to 103.8 m^2. The typical filling volume of each unit is 75 percent of the available operating volume. The material of construction is either carbon steel or 300 series stainless steel, with optional special metallurgy available.

In addition to many varied applications in the chemical industry, the reactotherm is widely used to process waste sludges which must be dried in order to landfill the solid components. In many of these cases, the solvents are valuable components of the waste stream and can be recovered and recycled.

The housing of the continuous model consists of two fully enclosed, cylindrical, flanged-vessel sections. The standard design of the housing is suitable for full vacuum (3–30 kPa abs) or pressures up to 7 bar abs (higher design pressures available). The housing sections, including both end covers, are jacketed for heating or cooling. Hot water, steam, or thermal oil may be used as the heating medium, with maximum temperature up to 350°C possible. Flanged ports and nozzles are provided for product feed and discharge, vapor removal, inspection, and for the stationary mixing elements. The design of the continuous models is such that the ratio of vessel length to housing diameter is approximately 6:1, resulting in a long unit with narrow diameter. Bearing supports are provided at both ends of the unit for shaft support.

The mixing bars in the continuous unit also convey the product through the unit, whereas the product filling level is determined by a weir flanged between the housing sections. The residence time and speed of the mixing shaft are specially matched to the requirements of the process.

The batch-operating units consist of only one jacketed, cylindrical vessel with the necessary nozzles and ports for product inlet and outlet, vapor, inspection, and mixing elements. The standard design of the housing is suitable for full vacuum or pressures up to 7 bar abs (higher design pressures available), with temperatures up to 350°C possible. The mixing bars are arranged such that a countercurrent flow in a radial direction of the product is achieved in the process vessel. For discharge of the material, a central port is provided at the bottom of the unit. The batch models up to 1080 liters volume are provided with cantilever-mounted mixing shafts. Above 1080 liters, the shaft is supported at both ends with bearings. The design of the batch models is such that the ratio of vessel length to housing diameter is approximately 2.5:1, resulting in a short unit with large diameter.

Design Methods for Reactotherm Product trials are conducted in small pilot dryers (8–60 liter batch or continuous units) to determine material handling and process-retention times. Variables such as drying temperature, pressure level, and shaft speed are analyzed during the test trials. For design purposes, the heat-transfer coefficient for the reactotherm is in the range of 10 $W/m^2 \cdot K$ (light, free-flowing powders) up to 150 $W/m^2 \cdot K$ (dilute slurries).

Hearth Furnaces A special design of a circular hearth furnace is the **Mannheim furnace,** in which sulfuric acid is reacted with sodium chloride to produce salt cake and hydrochloric acid. It consists of a refractory hearth, up to 6 m in diameter, with a silicon carbide arch. Hot flue gases are circulated around the muffle. The major portion of heat is transmitted through the arch and radiated to the product on the hearth. Feed materials are mixed and charged continuously to the center of the hearth, where they are stirred by underdriven rabble arms. The charge is gradually worked toward the periphery as the reaction generates hydrogen chloride gas. The gas is withdrawn through a separate duct to an absorption system. The salt cake is discharged at the periphery. Figure 12-82 shows a diagrammatic cross section of a Mannheim furnace. Combustion-chamber temperatures of about 1475 K are used for heating. The salt cake is discharged from the hearth at about 800 K.

Multiple-Hearth Furnaces Multiple-hearth furnaces are known under various names: the Herreshoff, McDougall, Wedge, Pacific, etc. Figure 12-83 shows a general design. It consists of a number of annular-shaped hearths mounted one above the other. There are rabble arms on each hearth driven from a common center shaft. The feed is charged at the center of the upper hearth. The arms move the charge outward to the periphery, where it falls to the next hearth. Here it is moved again to the center, from which it falls to the next hearth. This continues down the furnace. The hollow center shaft is cooled internally by forced-air circulation.

Burners may be mounted at any of the hearths, and the circulated air is used for combustion. These furnaces handle granular materials and provide a long countercurrent path between the flue gases and the charge material. Industrial sizes are built from 2 to 7 m in diameter and include 4 to 16 hearths. Total hearth areas range from 6.5 to 335 m^2. The furnaces are used for roasting ores, drying and calcining lime, magnesite, and carbonate sludges, reactivation of decolorizing earths, and burning of sulfides to produce sulfur dioxide. The following is a partial list of applications:

1. Lime (*a*) from crushed limestone, (*b*) from oyster or sea shell, and (*c*) from dolomitic limestone
2. Lead and zinc; roasting of sulfides
3. Mercury from cinnabar ores by volatilization
4. Gold and silver: (*a*) chloridizing roast of gold-silver ore, and (*b*) removal of arsenic
5. Sulfuric acid from iron pyrites
6. Paint pigments; roasting of metallic oxides
7. Refractory clays; calcination of refractory clay to reduce shrinkage
8. Foundry sand; removal of carbon from used foundry sand
9. Fuller's earth; calcination of fuller's-earth material
10. Sewage disposal; calcination of sewage slurry

Table 12-31 lists three specific applications with a brief description of the furnaces as to design and operating conditions.

GRAVITY DRYERS

Description A body of solids in which the particles, consisting of granules, pellets, beads, or briquettes, flow downward by gravity at

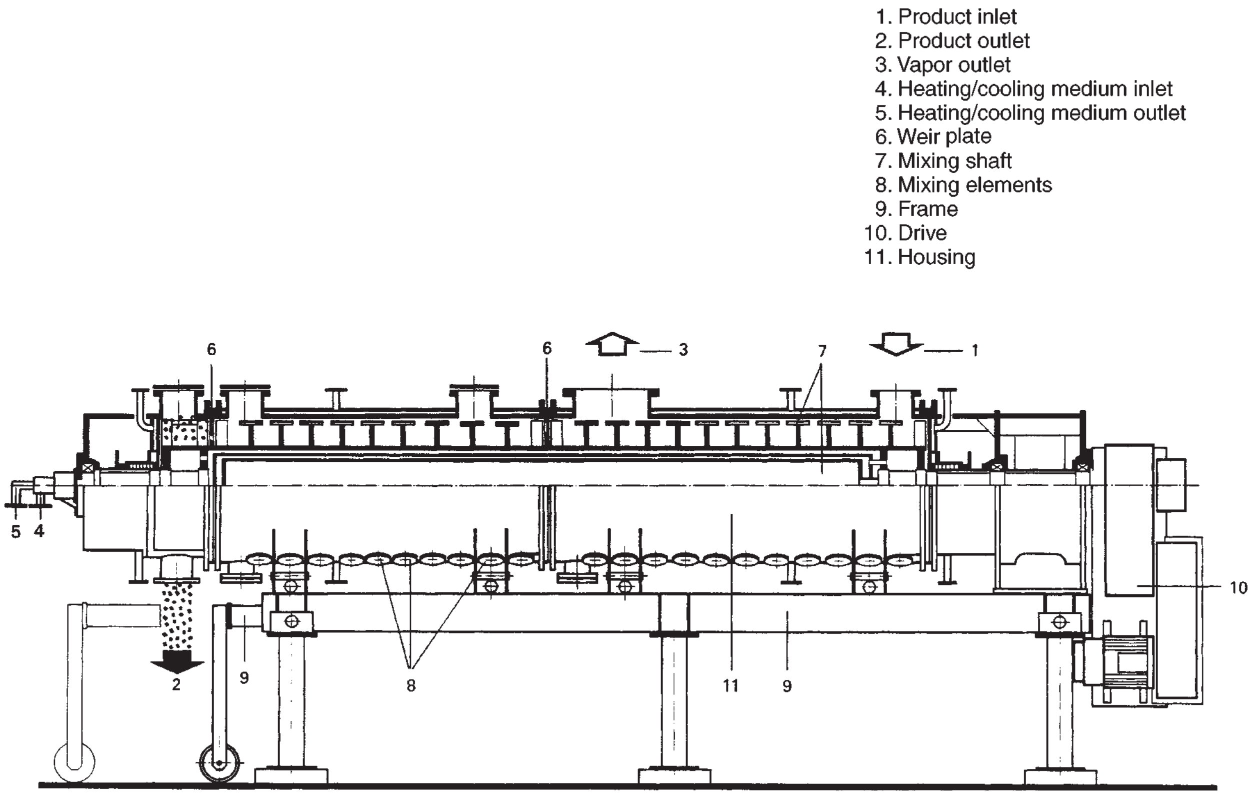


FIG. 12-81 Continuous indirect-heated reactotherm. (*Krauss Maffei.*)

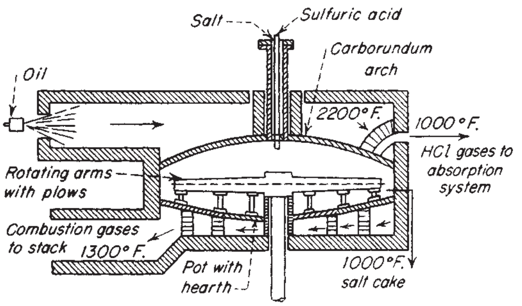


FIG. 12-82 Mannheim-type mechanical hydrochloric acid furnace.

substantially their normal settled bulk density through a vessel in contact with gases is defined frequently as a **moving bed.** Moving-bed equipment finds application in blast furnaces, shaft furnaces, and petroleum refining.

A gravity dryer consists of a stationary vertical, usually cylindrical housing with openings for the introduction of solids (at the top) and removal of solids (at the bottom). Gas flow is through the solids bed and may be cocurrent or countercurrent and, in some instances, crossflow. By definition, the rate of gas flow upward must be less than that required for fluidization.

Fields of Application One of the major advantages of the gravity-bed technique is that it lends itself well to true intimate countercurrent contacting of solids and gases. This provides for efficient heat transfer and mass transfer. Gravity-bed contacting also permits the use of the solid as a heat-transfer medium, as in pebble heaters.

Gravity vessels are applicable to coarse granular free-flowing solids which are comparatively dust-free. The solids must possess physical properties in size and surface characteristics so that they will not stick together, bridge, or segregate during passage through the vessel. The presence of significant quantities of fines or dust will close the passages among the larger particles through which the gas must penetrate, increasing pressure drop. Fines may also segregate near the sides of the bed or in other areas where gas velocities are low, ultimately completely sealing off these portions of the vessel. The high efficiency of gas-solids contacting in gravity beds is due to the uniform distribution of gas throughout the solids bed; hence choice of feed and its preparation are important factors to successful operation. Preforming techniques such as pelleting and briquetting are employed frequently for the preparation of suitable feed materials.

Gravity vessels are suitable for low-, medium-, and high-temperature operation; in the last case, the housing will be lined completely with refractory brick. Dust-recovery equipment is minimized in this type of operation since the bed actually performs as a dust collector itself, and dust in the bed will not, in a successful application, exist in large quantities.

Other advantages of gravity beds include flexibility in gas and solids flow rates and capacities, variable retention times from minutes to several hours, space economy, ease of startup and shutdown, the potentially large number of contacting stages, and ease of control by using the inlet- and exit-gas temperatures.

Maintenance of a uniform rate of solids movement downward over the entire cross section of the bed is one of the most critical operating problems encountered. For this reason gravity beds are designed to be as high and narrow as practical. In a vessel of large cross section, discharge through a conical bottom and center outlet will usually result in some degree of “ratholing” through the center of the bed. Flow through the center will be rapid while essentially stagnant pock-

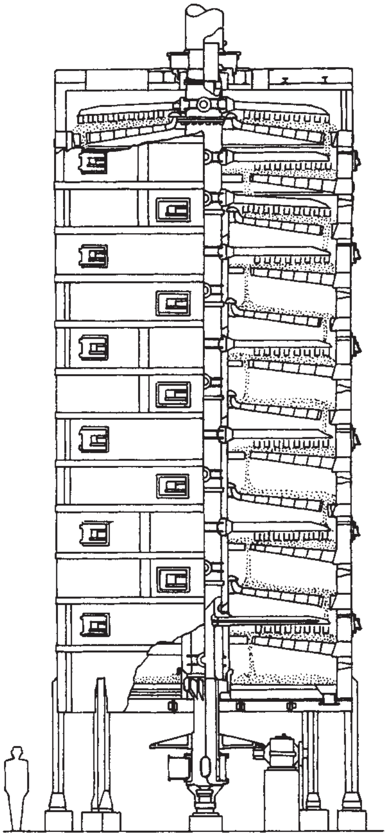


FIG. 12-83 Pacific multiple-hearth furnace.

ets are left around the sides. To overcome this problem, multiple outlets are provided in the center and around the periphery; table unloaders, rotating plows, wide moving grates, and multiple-screw unloaders are employed; insertion of inverted cone baffles in the lower section of the bed, spaced so that flushing at the center is retarded, is also a successful method for improving uniformity of solids movement. Figure 12-84 illustrates a moving tray with multiple downspouts used to remove a precise amount of solids from each increment of area across the base of a gravity-bed reactor. The various pockets are filled at one extremity of its motion and emptied at the other. It is suitable primarily for fine nonabrasive solids. Figure 12-85 depicts a perforated-plate design, taking advantage of the flow characteristics and angle of repose of the solids to control the unloading rate. Still another design of this general type involves the use of a nest of inclined pipes, discharging into a common header, and placed to draw solids at geometrically spaced points across the base of the reactor.

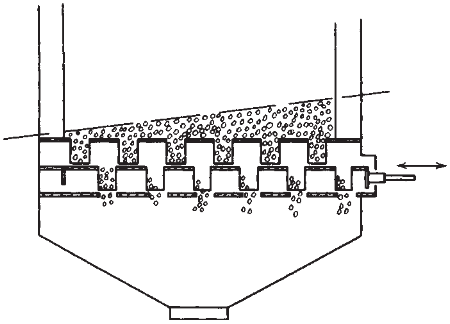


FIG. 12-84 Gravity-bed reactor; solids-discharge mechanism.

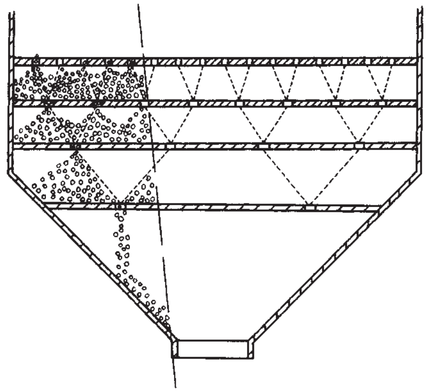


FIG. 12-85 Perforated-tray type of reactor-discharge control.

Gas disengaging from the solids may represent another serious operating problem in a gravity bed. One method employs downspouts at the top for solids feeding while leaving an open space in the vessel above the downspout outlet for gas disengaging, as illustrated in Fig. 12-86*a*. Another uses a series of inverted V-shaped channels inserted into the top of the solids bed. Gas and vapor are collected and removed from under the V's, while the solids flow over the top and around the channels (Fig. 12-86*b*). These methods for both gas and solids removal were developed originally for petroleum-refining catalytic reactors.

Shaft Furnaces The oldest and most important application of the shaft furnace is the **blast furnace** used for the production of pig iron. Another use is in the manufacture of phosphorus from phosphate rock. Formerly lime was calcined exclusively in this type of furnace. Shaft furnaces are widely used also as gas producers. Chemicals are manufactured in shaft furnaces from briquetted mixtures of the reacting components.

A shaft furnace is a vertical refractory-lined cylinder in which a stationary or descending column of solids is maintained and through

TABLE 12-31 Applications of Multiple-Hearth Furnaces*

Product	Production rate	Furnace size	Special features
Mercury from cinnabar ore	225 tons ore/day (95% recovery)	(2) 18.0 ft. diam., 8 hearth furnaces	Furnaces fired on hearths 3 to 7, inclusive; retention time of 1.0 hr.; furnaces are oil-fired with low-pressure atomizing air burners; all air, both primary and secondary, introduced through the burners; draft control by Monel cold-gas fans downstream from mercury condensers.
Lime from oyster shell	240 tons/day, shell (120 tons/day, lime)	(1) 22 ft., 3 in. diam., 12 hearth furnaces	
Magnesium oxide from magnesium hydroxide	100 tons/day, 50% magnesium hydroxide slurry; yields 50 tons/day magnesium oxide	(2) 22 ft., 3 in., 10 hearth furnaces	Furnace walls of 4.5-in. firebrick, 9-in. insulation for 1550°F. operating temp. Furnace fired on hearths 4 to 10, inclusive

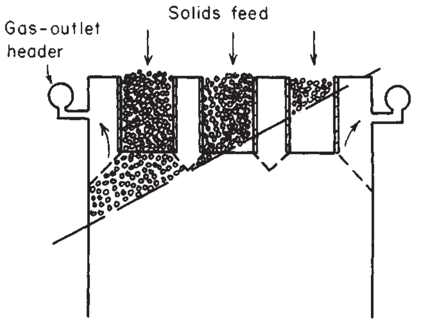


FIG. 12-86*a* Countercurrent gas-solids flow at the top disengaging section of a moving-bed catalytic reactor.

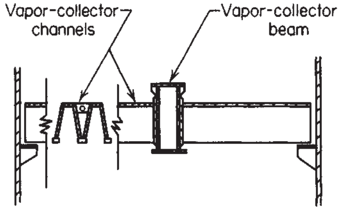


FIG. 12-86*b* Vapor disengaging tray at the top of a gravity-bed catalytic reactor. This design may also be employed for the addition of gas to a bed of solids.

which an ascending stream of hot gas is forced. Three methods of fuel application may be employed: (1) one in which a solid fuel is added alone or mixed with the reacting solids, (2) one in which the fuel is burned in a separate combustion chamber with the hot gases being blown into the furnace at some level of the column, (3) one in which the fuel is introduced and burned in the bottom of the shaft.

For maximum heat economy, recovered exhaust heat is employed for preheating of the incoming solids and combustion air. The fuels used may be gas, oil, or pulverized coal.

Bucket elevators, skip hoists, and cranes are used for top feeding of the furnace. Retention and downward flow are controlled by timing of the bottom discharge. Gases are propelled by a blower or by induced draft from a stack or discharge fan. In normal operation, the downward flow of solids and upward flow of gas are constant with time, maintaining ideal steady-state conditions.

Figure 12-87 illustrates a shaft lime kiln.

Design Methods for Shaft Furnaces The size and shape of the charge particles control the amount of surface over which heat may be transmitted to the particle and also the depth of penetration through which the heat must pass to reach the center of each particle. Also, this size and shape control the nature of the random packing in the shaft and the extent of voids for gas passage. As particle size is decreased, the surface area of the particles increases. At the same time, the depth of heat penetration decreases. Both these factors tend to improve performance. With small particle size, however, the charge column presents high resistance to the passage of gas.

With closely screened material, the percentage of voids (usually 37 percent) is independent of particle size. With unscreened particles showing a wide variation in size, the void volume is decreased; irregularity in gas flow results.

There is a large difference between the total surface of the particles (as determined by their size and shape) and the “effective surface” actually exposed to the passing gas stream. In practice, it has been estimated that as little as 10 to 25 percent of the total surface is effective in heat transfer when unscreened particles are treated.

Irregular-shaped particles exhibit greater surface area than regular-shaped cubes and spheres, the amount of this increase being possibly 25 percent. The effect of particle size and size distribution on effective surface, in a shaft employed for calcination of limestone, is shown in Fig. 12-88. Curve *A* shows the calculated surface based on an assumed 50 percent void volume and cubical-shaped particles. The *B* set of curves applies to such unscreened irregularly shaped particles as are usually encountered in practice.

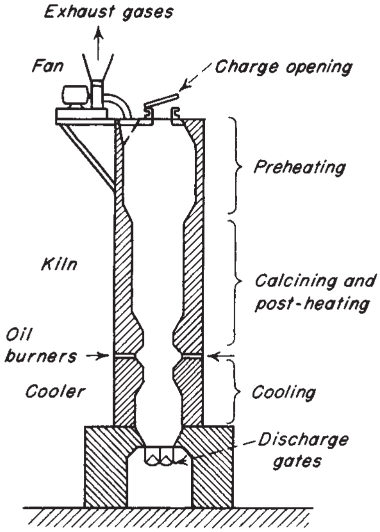


FIG. 12-87 Shaft furnace for lime production.

The laws governing the flow of fluids through packed beds given in Sec. 6 are applicable to shaft furnaces. Since the pressure drop in a bed is affected by the size and shape of the interstitial voids, the horizontal and vertical nonuniformity of the bed, the changes in gas composition during passage, and other operating factors, test data for a given material are necessary for proper design. In the case of limestone, Fig. 12-89 shows the effect of particle size on the gas-flow friction through the bed, assuming that the friction varies as the square of the gas mass velocity and inversely with the particle size, and utilizing

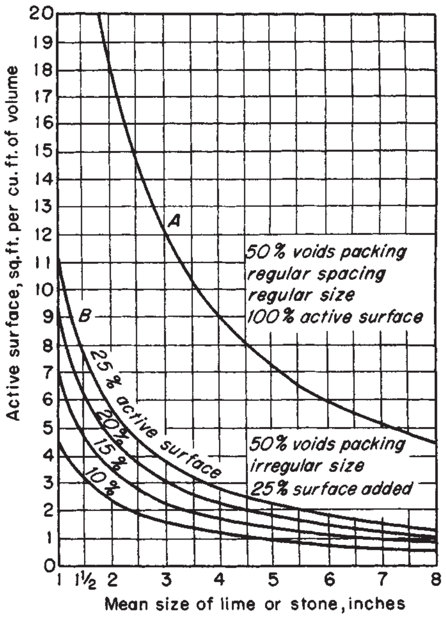


FIG. 12-88 Curve *A* shows surface variations with stone size, 100 percent active surfaces. Curves in group *B* show the effect of irregular stone size.

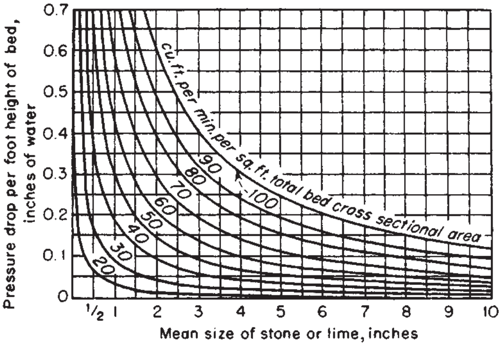


FIG. 12-89 Variation in gas friction with size of stone.

base points established during actual kiln operations. Information on the mathematical treatment of heat transfer in packed beds is included in Sec. 12.

Pellet Coolers and Dryers Gravity beds are employed for the cooling and drying of extruded pellets and briquettes from size-enlargement processes. The rotary cooler illustrated in Fig. 12-90 consists of a stationary steel tank having a wear cylinder at the top for entry of gas and solids (usually from a pneumatic conveyor), with air holes staggered around the outer wall to admit additional air for optimum circulation. The tank encloses a rotating cage for retention of the solids bed. This cage consists of an inner cylinder of wire mesh and an outer perforated shell. Air entering the tank is circulated in cross-flow through the pellet bed and discharges through the center column. Usually a rotary unloading gate and air lock are located underneath the cage.

Another cross-flow design employs a rectangular housing, partitioned into three vertical sections (Fig. 12-91). Solids move downward in the two outer sections, while cooling or drying air is drawn through the louvered outer walls and through the solids bed and is discharged through the center section. Solids are discharged over a baffled shaking shoe. Units of this general type are used for drying wheat and other grain products and numerous forms of pelleted feeds. Gravity-bed dryers are most suitable for drying of granular heat-sensitive products employing moderate air temperatures. These require extended holdup during the falling-rate drying period.

Spouted Beds The spouted-bed technique was developed primarily for solids which are too coarse to be handled in fluidized beds. Although their applications overlap, the methods of gas-solids mixing are completely different. A schematic view of a spouted bed is given in Fig. 12-92. Mixing and gas-solids contacting are achieved first in a fluid "spout," flowing upward through the center of a loosely packed bed of solids. Particles are entrained by the fluid and conveyed to the top of the bed. They then flow downward in the surrounding annulus as in an ordinary gravity bed, countercurrently to gas flow. The mechanisms of gas flow and solids flow in spouted beds were first described by Mathur and Gishler [*Am. Inst. Chem. Eng. J.*, **1**(2), 157–164 (1955)]. Drying studies have been carried out by Cowan [*Eng. J.*, **41,** 5, 60–64 (1958)], and a theoretical equation for predicting the minimum fluid velocity necessary to initiate spouting was developed by Madonna and Lama [*Am. Inst. Chem. Eng. J.*, **4**(4), 497 (1958)]. Investigations to determine maximum spoutable depths and to develop theoretical relationships based on vessel geometry and operating variables have been carried out by Lefroy [*Trans. Inst. Chem. Eng.*, **47**(5), T120–128 (1969)] and Reddy [*Can. J. Chem. Eng.*, **46**(5), 329–334 (1968)].

Gas flow in a spouted bed is partially through the spout and partially through the annulus. About 30 percent of the gas entering the system immediately diffuses into the downward-flowing annulus. Near the top of the bed, the quantity in the annulus approaches 66 percent of the total gas flow; the gas flow through the annulus at any point in the bed equals that which would flow through a loosely packed solids bed under the same conditions of pressure drop. Solids flow in the annulus is both downward and slightly inward. As the fluid spout rises in the bed, it entrains more and more particles, losing velocity and gas into the annulus. The volume of solids displaced by the spout is roughly 6 percent of the total bed.

On the basis of experimental studies, Mathur and Gishler derived an empirical correlation to describe the minimum fluid flow necessary for spouting, in 3- to 12-in-diameter columns:

$$u = \frac{D_p}{D_c}\left(\frac{D_o}{D_c}\right)^{0.33}\left[\frac{2gL(p_s - p_f)}{p_f}\right]^{0.5} \tag{12-62}$$

where u = superficial fluid velocity through the bed, ft/s; D_p = particle diameter, ft; D_c = column (or bed) diameter, ft; D_o = fluid-inlet orifice diameter, ft; L = bed height, ft; p_s = absolute solids density, lb/ft^3; p_f = fluid density, lb/ft^3; and g = 32.2 ft/s^2, gravity acceleration. To convert feet per second to meters per second, multiply by 0.305; to convert pounds per cubic foot to kilograms per cubic meter, multiply by 16. g = 9.8 m/s^2 in SI units. The inlet orifice diameter, air rate, bed diameter, and bed depth were all found to be critical and interdependent:

1. In a given-diameter bed, deeper beds can be spouted as the gas-inlet orifice size is decreased. Using air, a 12-in-diameter bed containing 0.125- by 0.250-in wheat can be spouted at a depth of over 100 in with a 0.8-in orifice, but at only 20 in with a 2.4-in orifice.

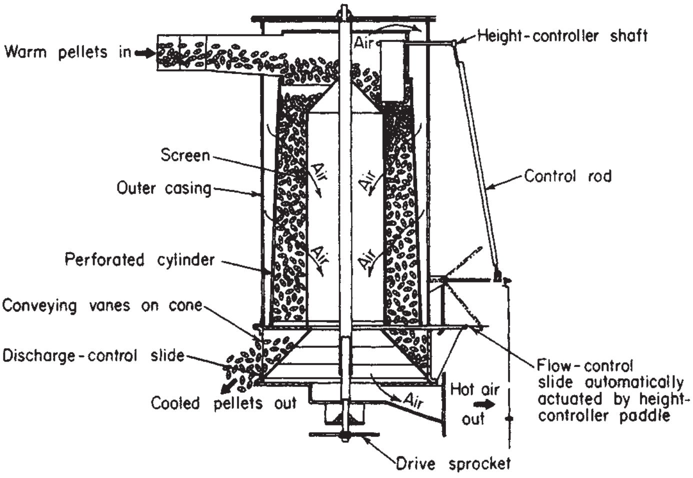


FIG. 12-90 Sprout, Waldron rotary cooler. (*Sprout, Waldron Cos.*)

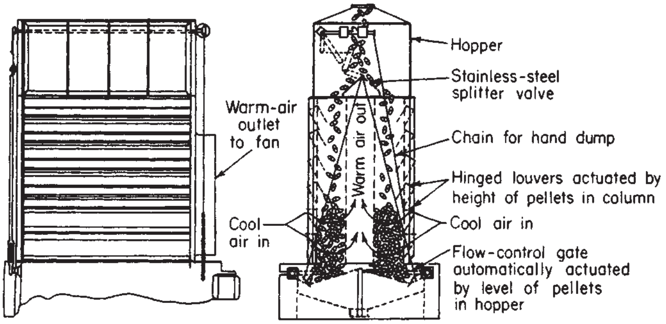


FIG. 12-91 Vertical gravity-bed cooler with louvres. (*Sprout, Waldron Co.*)

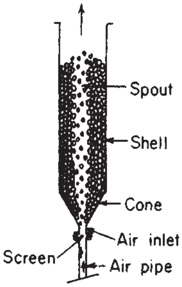


FIG. 12-92 Schematic diagram of a spouted bed. [*Mathur and Gishler,* Am. Inst. Chem. Eng. J., ***1,*** *2, 157 (1955).*]

2. Increasing bed diameter increases spoutable depth. By employing a bed-orifice diameter ratio of 12 for air spouting, a 9-in-diameter bed was spouted at a depth of 65 in while a 12-in-diameter bed was spouted at 95 in.

3. As indicated by Eq. (12-62) the superficial fluid velocity required for spouting increases with bed depth and orifice diameter and decreases as the bed diameter is increased.

Employing wood chips, Cowan's drying studies indicated that the volumetric heat-transfer coefficient obtainable in a spouted bed is at least twice that in a direct-heat rotary dryer. By using 20- to 30-mesh Ottawa sand, fluidized and spouted beds were compared. The volumetric coefficients in the fluid bed were 4 times those obtained in a spouted bed. Mathur dried wheat continuously in a 12-in-diameter spouted bed, followed by a 9-in-diameter spouted-bed cooler. A drying rate of roughly 100 lb/h of water was obtained by using 450 K inlet air. Six hundred pounds per hour of wheat was reduced from 16 to 26 percent to 4 percent moisture. Evaporation occurred also in the cooler by using sensible heat present in the wheat. The maximum drying-bed temperature was 118°F, and the overall thermal efficiency of the system was roughly 65 percent. Some aspects of the spouted-bed technique are covered by patent (U.S. Patent 2,786,280).

Cowan reported that significant size reduction of solids occurred when cellulose acetate was dried in a spouted bed, indicating its possible limitations for handling other friable particles.

DIRECT-HEAT VIBRATING-CONVEYOR DRYERS

Information on vibrating conveyors and their mechanical construction is given in Sec. 21. The vibrating-conveyor dryer is a modified form of fluidized-bed equipment, in which fluidization is maintained by a combination of pneumatic and mechanical forces. The heating gas is introduced into a plenum beneath the conveying deck through ducts and flexible hose connections, passes up through a screen, perforated, or slotted conveying deck, through the fluidized bed of solids, and into an exhaust hood (Fig. 12-93). If ambient air is employed for cooling, the sides of the plenum may be open and a simple exhaust system used; however, because the gas-distribution plate may be designed for several inches of water-pressure drop to ensure a uniform velocity distribution through the bed of solids, a combination pressure-blower-exhaust-fan system is desirable to balance the pressure above the deck with the outside atmosphere and prevent gas in-leakage or blowing at the solids feed and exit points.

Units are fabricated in widths from 0.3 to 1.5 m. Lengths are variable from 3 to 50 m; however, most commercial units will not exceed a length of 10 to 16 m per section. Power required for the vibrating drive will be approximately 0.4 kW/m^2 of deck.

In general, this equipment offers an economical heat-transfer area for first cost as well as operating cost. Capacity is limited primarily by the air velocity which can be used without excessive dust entrainment. Table 12-32 shows limiting air velocities suitable for various solids particles. Usually, the equipment is satisfactory for particles larger than 100 mesh in size. [The use of indirect-heated conveyors eliminates the problem of dust entrainment, but capacity is limited by the heat-transfer coefficients obtainable on the deck (see Sec. 11)].

When a stationary vessel is employed for fluidization, all solids being treated must be fluidized; nonfluidizable fractions fall to the bottom of the bed and may eventually block the gas distributor. The addition of mechanical vibration to a fluidized system offers the following advantages:

1. Equipment can handle nonfluidizable solids fractions. Although these fractions may drop through the bed to the screen, directional-throw vibration will cause them to be conveyed to the discharge end of the conveyor. Prescreening or sizing of the feed is less critical than in a stationary fluidized bed.

2. Because of mechanical vibration, incipient channeling is reduced.

3. Fluidization may be accomplished with lower pressures and gas velocities. This has been evidenced on vibratory units by the fact that fluidization stops when the vibrating drive is stopped.

Vibrating-conveyor dryers are suitable for free-flowing solids containing mainly surface moisture. Retention is limited by conveying speeds which range from 0.02 to 0.12 m/s. Bed depth rarely exceeds 7 cm, although units are fabricated to carry 30- to 46-cm-deep beds; these also employ plate and pipe coils suspended in the bed to provide additional heat-transfer area. Vibrating dryers are not suitable for fibrous materials which mat or for sticky solids which may ball or adhere to the deck.

For estimating purposes for direct-heat drying applications, it can be assumed that the average exit-gas temperature leaving the solids bed will approach the final solids discharge temperature on an ordinary unit carrying a 5- to 15-cm-deep bed. Calculation of the heat load and selection of an inlet-air temperature and superficial velocity (Table 12-32) will then permit approximate sizing, provided an approximation of the minimum required retention time can be made.

Vibrating conveyors employing direct contacting of solids with hot, humid air have also been employed for the agglomeration of fine powders, chiefly for the preparation of agglomerated water-dispersible food products. Control of inlet-air temperature and dew point permits the uniform addition of small quantities of liquids to solids by con-

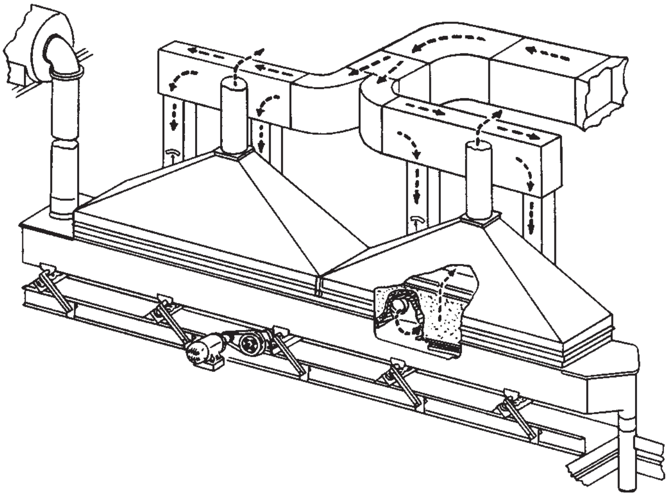


FIG. 12-93 Vibrating conveyor dryer. (*Carrier Division, Rexnord Inc.*)

densation on the cool incoming-particle surfaces. The wetting section of the conveyor is followed immediately by a warm-air-drying section and particle screening.

DISPERSION DRYERS

A gas-solids contacting operation in which the solids phase exists in a dilute condition is termed a **dispersion system.** It is often called a pneumatic system because, in most cases, the quantity and velocity of the gas are sufficient to lift and convey the solids against the force of gravity. Pneumatic systems may be distinguished by two characteristics:

1. Retention of a given solids particle in the system is on the average very short, usually no more than a few seconds. This means that any process conducted in a pneumatic system cannot be diffusion-controlled. The reaction must be mainly a surface phenomenon, or the solids particles must be very small so that heat transfer and mass transfer from the interiors are essentially instantaneous.
2. On an energy-content basis, the system is balanced at all times; i.e., there is sufficient energy in the gas (or solids) present in the system at any time to complete the work on all the solids (or gas) present at the same time. This is significant in that there is no lag in response to control changes or in starting up and shutting down the system; no partially processed residual solids or gas need be retained between runs.

It is for these reasons that pneumatic equipment is especially suitable for processing *heat-sensitive, easily oxidized, explosive,* or *flammable* materials which cannot be exposed to process conditions for extended periods.

Gas flow and solids flow are usually cocurrent, one exception being a countercurrent-flow spray dryer. The method of gas-solids contacting is best described as through circulation; however, in the dilute condition solids particles are so widely dispersed in the gas that they exhibit apparently no effect upon one another, and they offer essentially no resistance to the passage of gas among them.

TABLE 12-32 Table for Estimating Maximum Superficial Air Velocities through Vibrating-Conveyor Screens*

	Velocity, m/s	
Mesh size	2.0 specific gravity	1.0 specific gravity
200	0.22	0.13
100	0.69	0.38
50	1.4	0.89
30	2.6	1.8
20	3.2	2.5
10	6.9	4.6
5	11.4	7.9

*Carrier Division, Rexnord Inc.

Pneumatic-Conveyor Dryers A pneumatic-conveyor dryer consists of a long tube or duct carrying a gas at high velocity, a fan to propel the gas, a suitable feeder for addition and dispersion of particulate solids in the gas stream, and a cyclone collector or other separation equipment for final recovery of solids from the gas.

The solids feeder may be of any type; screw feeders, venturi sections, high-speed grinders, and dispersion mills are employed. For pneumatic conveyors, selection of the correct feeder to obtain thorough initial dispersion of solids in the gas is of major importance. For example, by employing an air-swept hammer mill in a drying operation, 65 to 95 percent of the total heat may be transferred within the mill itself if all the drying gas is passed through it. Fans may be of the induced-draft or the forced-draft type. The former is usually preferred because the system can then be operated under a slight negative pressure. Dust and hot gas will not be blown out through leaks in the equipment. Cyclone separators are preferred for low investment. If maximum recovery of dust or noxious fumes is required, the cyclone may be followed by a wet scrubber or bag collector.

In ordinary heating and cooling operations, during which there is no moisture pickup, continuous recirculation of the conveying gas is frequently employed. Also, solvent-recovery operations employing continuously recirculated inert gas with intercondensers and gas reheaters are carried out in pneumatic conveyors.

Pneumatic conveyors are suitable for materials which are granular and free-flowing when dispersed in the gas stream, so they do not stick on the conveyor walls or agglomerate. Sticky materials such as filter cakes may be dispersed and partially dried by an air-swept disintegrator in many cases. Otherwise, dry product may be recycled and mixed with fresh feed, and then the two dispersed together in a disintegrator. Coarse material containing internal moisture may be subjected to fine grinding in a hammer mill. The main requirement in all applications is that the operation be instantaneously completed; internal diffusion of moisture must not be limiting in drying operations, and particle sizes must be small enough so that the thermal conductivity of the solids does not control during heating and cooling operations. Pneumatic conveyors are rarely suitable for abrasive solids. Pneumatic conveying can result in significant particle-size reduction, particularly when crystalline or other friable materials are being handled. This may or may not be desirable but must be recognized if the system is selected. The action is similar to that of a fluid-energy grinder.

Pneumatic conveyors may be single-stage or multistage. The former is employed for evaporation of small quantities of surface moisture. Multistage installations are used for difficult drying processes, e.g., drying heat-sensitive products containing large quantities of moisture and drying materials initially containing internal as well as surface moisture. Typical single- and two-stage drying systems are illustrated in Figs. 12-94, 12-95*a* and *b*, and 12-96. Figure 12-94 incorporates a single-stage dryer with a second stage containing a cage-mill disintegrator. The second stage ensures complete drying after thorough dispersion of lumps and agglomerates. If disintegration is required to disperse the wet feed, the stages can be reversed, or disintegration can be employed in both stages. Systems of the type illustrated are employed for drying synthetic resins, of which low-pressure polyethylene and polypropylene are examples.

Figure 12-96 illustrates a single-stage dryer employing a paddle mixer, recycle, and an ABB Raymond cage mill for fine grinding and dispersion of the mixed feed in the air stream. These units are designed to handle filter and centrifuge cakes and other sticky or pasty feeds. Capacities are given in Table 12-33.

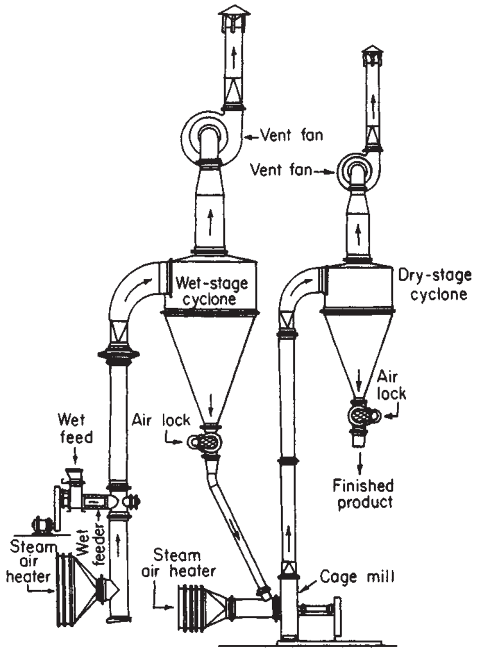


FIG. 12-94 Two-stage air-stream and cage mill, pneumatic-conveyor dryer. (*ABB Raymond.*)

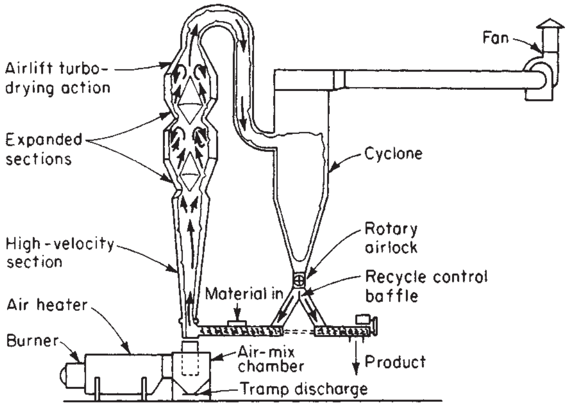


FIG. 12-95*a* Air-lift pneumatic-conveyor dryer; includes partial recycle of dry product and expanding tube and cone sections to provide longer holdup for coarse particles. (*Bepex Corp.*)

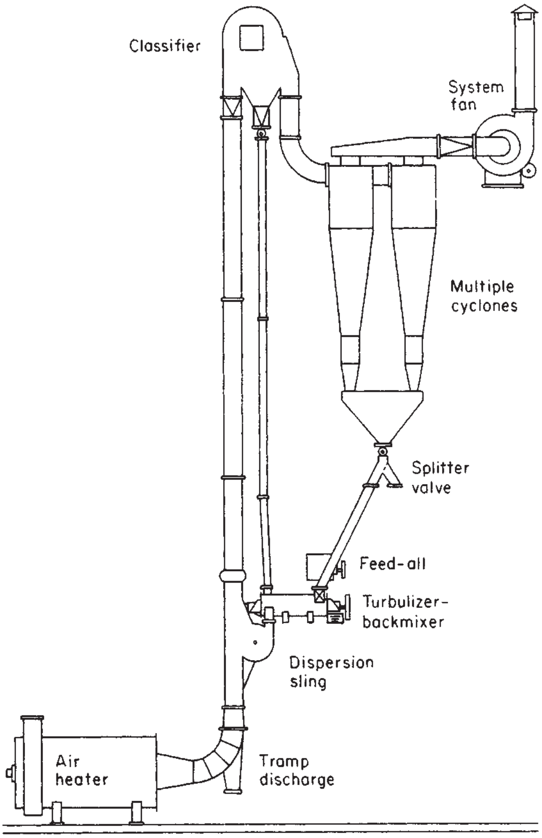


FIG. 12-95*b* Strong-Scott flash dryer with integral coarse-fraction classifier to separate undried particles for recycle. (*Bepex Corp.*)

Several typical products dried in pneumatic conveyors are described in Table 12-34. The air-stream type referred to is an ordinary single-stage dryer like the first stage of Fig. 12-94.

Design Methods for Pneumatic-Conveyor Dryers Depending upon the temperature sensitivity of the product, inlet-air temperatures between 400 and 1000 K are employed. With a heat-sensitive solid, a high initial moisture content should permit use of a high inlet-air temperature. Evaporation of surface moisture takes place at essentially the wet-bulb air temperature. Until this has been completed, by which time the air will have cooled significantly, the surface-moisture film prevents the solids temperature from exceeding the wet-bulb temperature of the air. Pneumatic conveyors are used for solids having initial moisture contents ranging from 3 to 90 percent, wet basis. The air quantity required and solids-to-gas loading are fixed by the moisture load, the inlet-air temperature, and, frequently, the exit-air humidity. If the last is too great to permit complete drying, i.e., if the exit-air humidity is above that in equilibrium with the product at required dryness, the solids-to-gas loading must be reduced together with the inlet-air temperature.

The gas velocity in the conveying duct must be sufficient to convey the largest particle. This may be calculated accurately by methods given in Sec. 12. For estimating purposes, a velocity of 25 m/s, calculated at the exit-air temperature, is frequently employed. If mainly surface moisture is present, the temperature driving force for drying will approach the log mean of the inlet- and exit-gas wet-bulb depressions. (The exit solids temperature will approach the exit-gas dry-bulb temperature.)

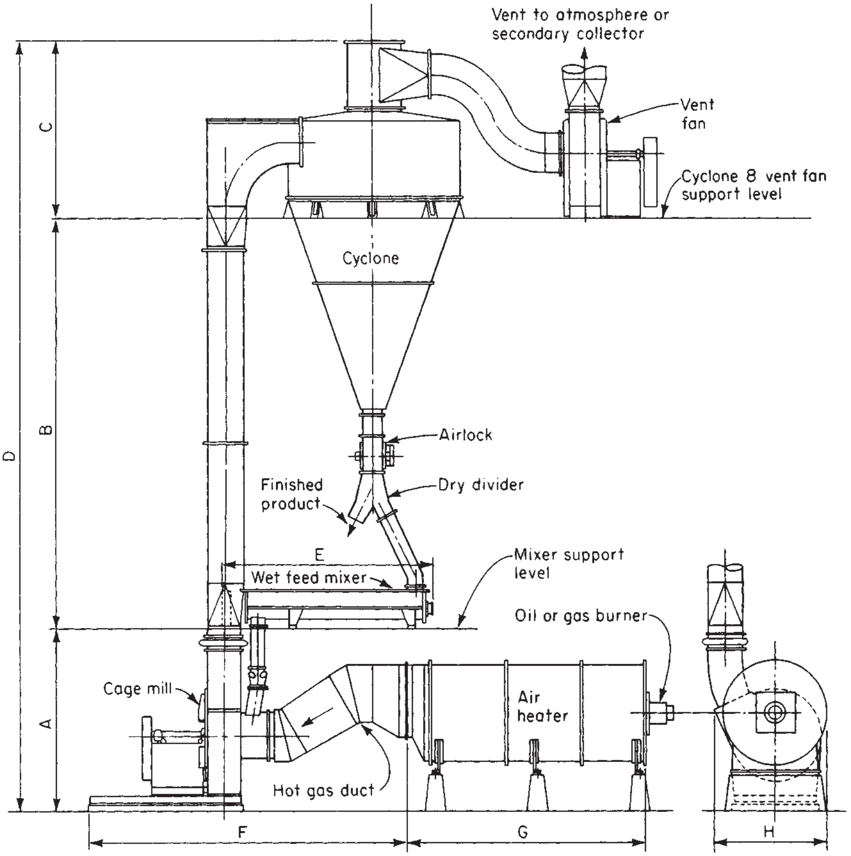


FIG. 12-96 Single-stage pneumatic-conveyor dryer. (*ABB Raymond.*)

Observation of operating conveyors indicates that the solids are rarely uniformly dispersed in the gas phase. With infrequent exceptions, the particles move in a laminar pattern, following a streamline along the duct wall where the flow velocity is at a minimum. Complete or even partial diffusion in the gas phase is rarely experienced even with low-specific-gravity particles. Air velocities may approach 20 to 30 m/s. It is doubtful, however, that even finer and lighter materials reach more than 80 percent of this speed, while heavier and larger fractions may travel at much slower rates [Fischer, *Mech. Eng.*, **81**(11), 67–69 (1959)]. Very little information and operating data on pneumatic-conveyor dryers which would permit a true theoretical basis for design have been published. Therefore, firm design always requires pilot tests. It is believed, however, that the significant velocity effect in a pneumatic conveyor is the difference in velocities between gas and solids, which is the reason why a major part of the total drying actually occurs in the feed section.

TABLE 12-33 Sizes and Capacities of ABB-Raymond Cage-Mill Flash-Drying Systems*

Based upon 1200°F inlet temperatures†

Cyclone	*A*	*B*	*C*	*D*	*E*	*F*	*G*	Approximate weight, lb *H*	Evaporation capacity, lb water/h†	Price,‡ FOB shops
18 ft 0 in	18 ft 0 in	38 ft 0 in	20 ft 0 in	76 ft 0 in	19 ft 6 in	49 ft 6 in	10 ft 0 in	115,000	20,000	$550,000
16 ft 0 in	15 ft 0 in	34 ft 0 in	17 ft 4 in	66 ft 4 in	17 ft 0 in	45 ft 6 in	9 ft 9 in	85,000	15,700	475,000
14 ft 0 in	14 ft 0 in	31 ft 0 in	14 ft 4 in	59 ft 4 in	16 ft 6 in	43 ft 4 in	9 ft 6 in	75,000	12,000	400,000
12 ft 0 in	13 ft 0 in	29 ft 0 in	12 ft 6 in	54 ft 6 in	15 ft 3 in	40 ft 4 in	8 ft 2 in	65,000	8,850	375,000
10 ft 0 in	11 ft 6 in	26 ft 0 in	10 ft 9 in	48 ft 3 in	13 ft 3 in	37 ft 8 in	7 ft 1 in	50,000	6,150	325,000
9 ft 0 in	11 ft 0 in	24 ft 0 in	10 ft 3 in	45 ft 3 in	13 ft 3 in	36 ft 8 in	6 ft 11 in	45,000	5,000	300,000
8 ft 0 in	10 ft 6 in	24 ft 0 in	9 ft 6 in	44 ft 0 in	12 ft 6 in	33 ft 11 in	6 ft 6 in	37,000	3,940	285,000
7 ft 0 in	10 ft 0 in	23 ft 0 in	8 ft 9 in	41 ft 9 in	12 ft 6 in	32 ft 3 in	6 ft 3 in	32,000	3,000	270,000
6 ft 0 in	9 ft 6 in	22 ft 0 in	8 ft 0 in	39 ft 6 in	11 ft 0 in	30 ft 9 in	5 ft 7 in	28,000	2,220	250,000
5 ft 0 in	9 ft 0 in	20 ft 0 in	7 ft 3 in	36 ft 3 in	10 ft 9 in	28 ft 4 in	5 ft 5 in	21,000	1,540	230,000
4 ft 0 in	8 ft 6 in	19 ft 0 in	6 ft 3 in	33 ft 9 in	10 ft 9 in	27 ft 1 in	4 ft 0 in	17,000	985	210,000

*ABB Raymond

†With inlet temperature of 600 to 700°F, consider the water evaporation to be one-half of that listed in the table. Considerably lower inlet temperatures are also frequently used for many materials.

‡Price based upon carbon steel construction (motors and secondary dust collectors by others). (1994)

TABLE 12-34 Typical Products Dried in Pneumatic-Conveyor Dryers*

Material	Initial moisture, wet basis, %	Final moisture, wet basis, %	Remarks
Clay, acid-treated	60	18	Cage-mill type
Coal, 1 cm × 0	11.5	1.5	Air-stream type
Corn-gluten feed	65	20	Cage-mill type
Kaolin (H_2O washed and partially dried)	10	0.5	Imp-mill type; grind to 99.9%—325 mesh
Gluten (vital wheat)	70	10	Imp-mill type; grind to—80 mesh
Clay, ball	25	0.5	Imp-mill type; grind to 95%—100 mesh
Gypsum, raw	25 total	5	Imp-mill type; grind and calcine to stucco
Pharmaceuticals	15	4	Air-stream type
Silica-gel catalyst	53	10	Cage-mill type
Synthetic resin	50	0.5	Two-stage system
Carboxymethyl cellulose	40	3	Imp-mill type; grind to 80%—200 mesh
Sewage sludge	82	0	Cage-mill-type

*ABB Raymond

One manner in which size may be computed, for estimating purposes, is by employing a volumetric heat-transfer concept as used for rotary dryers. If it is assumed that contacting efficiency is in the same order as that provided by efficient lifters in a rotary dryer and that the velocity difference between gas and solids controls, Eq. (12-52) may be employed to estimate a volumetric heat-transfer coefficient. By assuming a duct diameter of 0.3 m (D) and a gas velocity of 23 m/s, if the solids velocity is taken as 80 percent of this speed, the velocity difference between the two would be 4.6 m/s. If the exit gas has a density of 1 kg/m^3, the relative mass flow rate of the gas G becomes 4.8 kg/(s·m^2); the volumetric heat-transfer coefficient is 2235 J/(m^3·s·K). This is not far different from many coefficients found in commercial installations; however, it is usually not possible to predict accurately the actual difference in velocity between gas and solids. Furthermore, the coefficient is influenced by the solids-to-gas loading and particle size, which control the total solids surface exposed to the gas. Therefore, the figure given is only an approximation.

For estimating purposes, the conveyor cross section is fixed by the assumed air velocity and quantity. The volume, hence the length, can then be calculated by the method just presented, employing the log-mean air wet-bulb depression for the temperature driving force. A conveyor length >50 diameters is rarely required. Scale-up of pneumatic conveying dryers is outlined in a theoretical model which predicts dryer performance but which depends on uncertain parameters such as wall friction and agglomeration. [I. C. Kemp [*Drying Technology—An International Journal,* **12**(1&2), 279 (1994)].

Pressure drop in the system may be computed by methods described in Sec. 6. To prevent excessive leakage into or out of the system, which may have a total pressure drop of 20 to 38 cm of water, rotary air locks or screw feeders are employed at the solids inlet and discharge.

The conveyor and collector parts are thoroughly insulated to reduce heat losses in drying and other heating operations. Operating control is maintained usually by control of the exit-gas temperature, with the inlet-gas temperature varied to compensate for changing feed conditions. A constant solids feed rate must be maintained.

Cost Data for Pneumatic-Conveyor Dryers Purchase costs vary widely; many pneumatic-conveyor installations are assembled units, each component being purchased from a different supplier. Representative prices are given in Table 12-33 for conventional pneumatic-conveyor dryers. These include a cage mill for disintegration and a primary cyclone collector. In general, pneumatic conveyors for similar duties will compete in cost with cocurrent rotary dryers. Space economics may reduce the total installed investment slightly below that of the rotary unit. Operating costs, thermal efficiency, etc., are similar to those of cocurrent rotary units sized for the same duty. When other operations, such as conveying, grinding, or classifying, are simultaneously performed, operating and investment costs may be reduced for the pneumatic-drying process itself by being partially written off on the secondary function. In this situation, a pneumatic conveyor becomes particularly attractive.

Ring Dryers The ring dryer is a development of flash, or pneumatic-conveyor, drying technology, designed to increase the versatility of application of this technology and overcome many of its limitations. One of the great advantages of flash drying is the very short retention time, typically no more than a few seconds. However, in a conventional flash dryer, residence time is fixed and this limits its application to materials in which the drying mechanism is not diffusion controlled and where a range of moisture within the final product is acceptable. The ring dryer offers two advantages over the flash dryer. Principally there is control of residence time by the use of an adjustable internal classifier which allows fine particles, which dry quickly, to leave, while larger particles, which dry slowly, have an extended residence time within the system. Second, the combination of the classifier with an internal mill can allow simultaneous grinding and drying with control of product particle size and moisture. Available with a range of different feed systems to handle a variety of applications, the ring dryer provide wide versatility.

The essential difference between a conventional flash dryer and the ring dryer is the "manifold centrifugal classifier." The manifold pro-

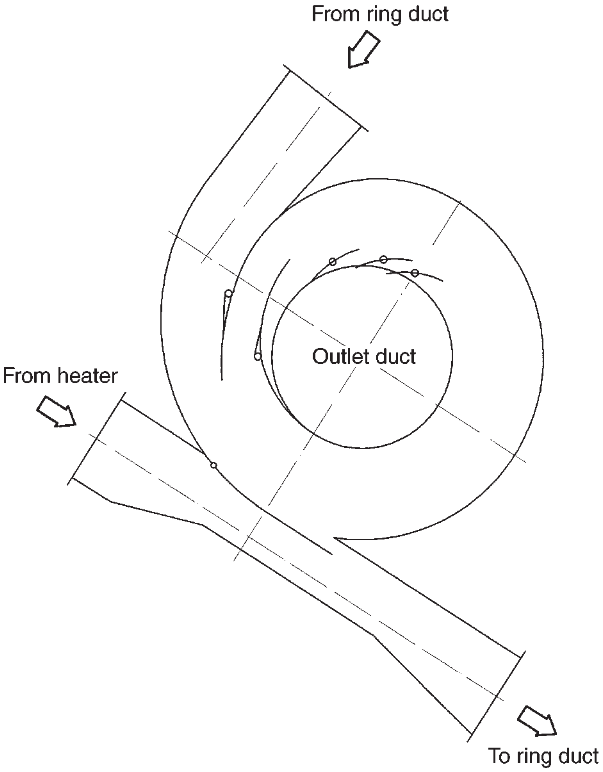


FIG. 12-97 Full manifold classifier for ring dryer. (*Barr—Rosin*)

vides classification of the product about to leave the dryer using differential centrifugal force. The manifold, as shown in Fig. 12-97, uses the centrifugal effect of an air stream passing around the curve to concentrate the product into a moving layer, with the dense material on the bottom and the light material on the top. This enables the adjustable splitter blades within the manifold classifier to segregate the heavier, wetter material and return it for a further circuit of drying. Fine, dried material is allowed to leave the dryer with the exhaust air and pass to the product collection system. This selective extension of residence time ensures a more evenly dried material than possible from a conventional flash dryer. Many materials which have traditionally been regarded as difficult to dry can be processed to the required moisture content in a ring dryer.

The recycle requirements of products in different applications can vary substantially depending upon the scale of operation, the ease of drying, and the finished-product specification. The location of reintroduction of undried material back into the drying medium has a significant impact upon the dryer performance and final-product characteristics.

Three configurations of the ring dryer have been developed to offer flexibility in design and optimal performance:

1. *Single-stage manifold—vertical configuration.* The feed ring dryer (see Fig. 12-98) is similar to a flash dryer but incorporates a single-stage classifier, which diverts 40–60 percent of the product back to the feed point. The feed ring dryer is ideally suited for materials which are neither heat sensitive nor require a high degree of classification. An advantage of this configuration is that it can be manufactured to very large sizes to achieve high-evaporative capacities.
2. *Full manifold—horizontal configuration.* The full ring dryer (see Fig. 12-99) incorporates a multistage classifier which allows much higher recycle rates than the single-stage manifold. This configuration usually incorporates a disintegrator which provides adjustable amounts of product grinding depending upon speed and manifold setting. For sensitive or fine materials, the disintegrator can be omitted. Alternative feed locations are available to suit the material sensitivity and the final-product requirements. The full ring configuration gives a very high degree of control of both residence time and particle size, and is used for a wide variety of applications from small production rates of pharmaceutical and fine chemicals to large production rates of food products, bulk chemicals, and minerals. This is the most versatile configuration of the ring dryer.
3. *P-type manifold—vertical configuration.* The P ring dryer (see Fig. 12-100) incorporates a single-stage classifier and was developed specifically for use with heat-sensitive materials. The undried material is reintroduced into a cool part of the dryer in which it recirculates until it is dry enough to leave the circuit.

An important element in optimizing the performance of a flash or ring dryer is the degree of dispersion at the feed point. Maximizing the product surface area in this region of highest evaporative driving force is a key objective in the design of this type of dryer. Ring dryers are fed using similar equipment to conventional flash dryers. Ring dryers with vertical configuration are normally fed by a flooded screw and a disperser which propels the wet feed into a high-velocity venturi, in which the bulk of the evaporation takes place. The full ring dryer normally employs an air-swept disperser or mill within the drying circuit to provide screenless grinding when required. Together with the manifold classifier this ensures a product with a uniform particle size. For liquid, slurry, or pasty feed materials, backmixing of the feed with a portion of the dry product will be carried out in order to produce a conditioned friable material. This further increases the versatility of the ring dryer, allowing it to handle sludge and slurry feeds with ease.

Dried product is collected in either cyclones or baghouses depending upon the product-particle size. When primary collection is carried out in cyclones, secondary collection in a baghouse or scrubber is usually necessary in order to comply with environmental regulations. A rotary valve is used to provide an airlock at the discharge point. Screws are utilized to combine product from multiple cyclones or large baghouses. If required, a portion of the dried product is separated from the main stream and returned to the feed system for use as backmix.

Design Methods for Ring Dryers Depending on the temperature sensitivity of the material to be processed, air inlet temperatures as high as 1400°F can be utilized. Even with heat-sensitive solids a high feed-moisture content may permit the use of a high air-inlet temperature since evaporation of surface moisture takes place at the wet-bulb air temperature. Until the surface moisture has been removed it will prevent the solids temperature from exceeding the air wet-bulb temperature, by which time the air will generally have cooled significantly. Ring dryers have been used to process materials with feed-moisture contents between 2–95 percent, weight fraction. The product-moisture content has been controlled to values from 20 percent down to less than 1 percent. The air velocity required and air-to-solids ratio are determined by the evaporative load, the air-inlet temperature, and the exhaust-air humidity. Too high an exhaust-air humidity would prevent complete drying so a lower air-inlet temperature and air-to-solids ratio would be required. The air velocity within the dryer must be sufficient to convey the largest particle, or agglomerate. The air-to-solids ratio must be high enough to convey both the product and backmix, together with internal recycle from the manifold. For estimating purposes a velocity of 5000 ft/min, calculated at dryer exhaust conditions, is appropriate both for pneumatic-conveyor and ring dryers. Sizes, capacity, and costs for full manifold ring dryers are described on Table 12-35.

Spray Dryers A spray dryer consists of a large cylindrical and usually vertical chamber into which material to be dried is sprayed in the form of small droplets and into which is fed a large volume of hot gas sufficient to supply the heat necessary to complete evaporation of the liquid. Heat transfer and mass transfer are accomplished by direct contact of the hot gas with the dispersed droplets. After completion of drying, the cooled gas and solids are separated. This may be accomplished partially at the bottom of the drying chamber by classification and separation of the coarse dried particles. Fine particles are separated from the gas in external cyclones or bag collectors. When only the coarse-particle fraction is desired for finished product, fines may be recovered in wet scrubbers; the scrubber liquid is concentrated and returned as feed to the dryer. Horizontal spray chambers are manufactured with a longitudinal screw conveyor in the bottom of the drying chamber for continuous removal of settled coarse particles.

The principal use of spray dryers is for ordinary drying of water solutions and slurries. They are used also in combined drying and heat-treating operations, and for melt fusion and cooling of molten materials, e.g., ammonium nitrate *prilling.* The latter may be considered a solids size-enlargement process. Spray dryers are employed for wet-agglomeration processes to produce rapidly dispersible forms of concentrated food products, another form of size enlargement. In contacting performance, the spray dryer is similar to a pneumatic conveyor. It differs in application in that the feed material is usually a liquid solution, slurry, or paste capable of being dispersed in a fluidlike spray (rather than being composed of free-flowing particulate solids).

Spray drying involves three fundamental unit processes: (1) liquid atomization, (2) gas-droplet mixing, and (3) drying from liquid droplets. Atomization is accomplished usually by one of three atomizing devices: (1) high-pressure nozzles, (2) two-fluid nozzles, and (3) high-speed centrifugal disks. With these atomizers, thin solutions may be dispersed into droplets as small as 2 μm. The largest drop sizes rarely exceed 500 μm (35 mesh). Because of the large total drying surface and small droplet sizes created, the actual drying time in a spray dryer is measured in seconds. Total residence of a particle in the system is on the average not more than 30 s. A review by Marshall [“Atomization and Spray Drying,” *Chem. Eng. Prog. Monogr. Ser.,* **50,** 2 (1954)] considers spray-drying theory in detail as well as the design and operating characteristics of modern spray dryers. A later survey of spray drying, which constitutes a good supplement to Marshall, was published by Masters [*Ind. Eng. Chem.,* **60**(10), 53–63 (1968)]. A more recent article summarizing scale-up of spray dryers has also been published by K. Masters [*Drying Technology—An International Journal,* **12**(1&2), 235 (1994)]. Recently there has been considerable interest in the scale-up and analysis of spray dryers using computational fluid dynamics. D. E. Oakley [*Drying Technology—An International Journal,* **12**(1&2), 217 (1994)]. Liquid atomization and dispersion are discussed in detail in Sec. 14. Atomizers commonly employed on spray dryers are described briefly in the following paragraphs.

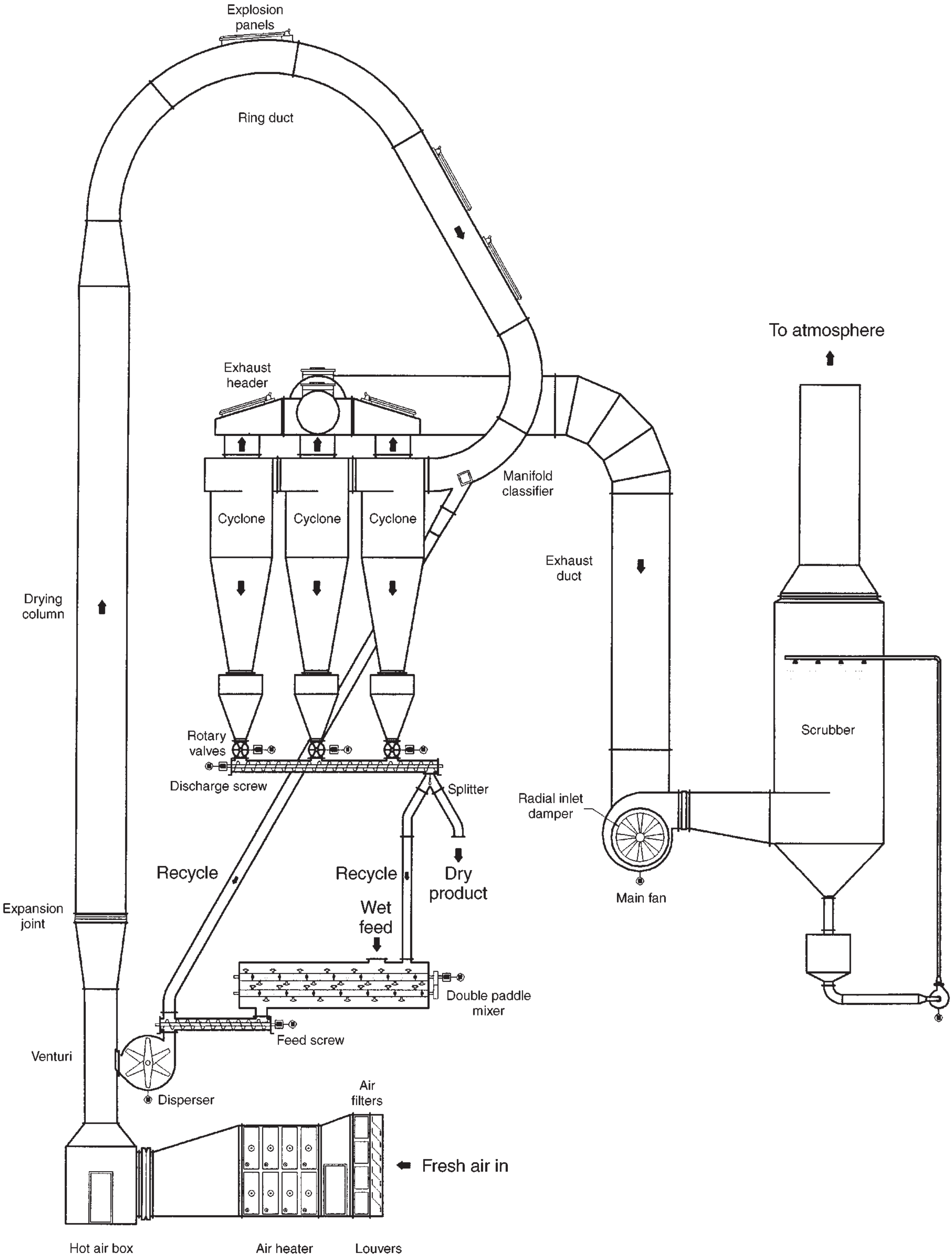


FIG. 12-98 Feed-type ring dryer. (*Barr—Rosin*)

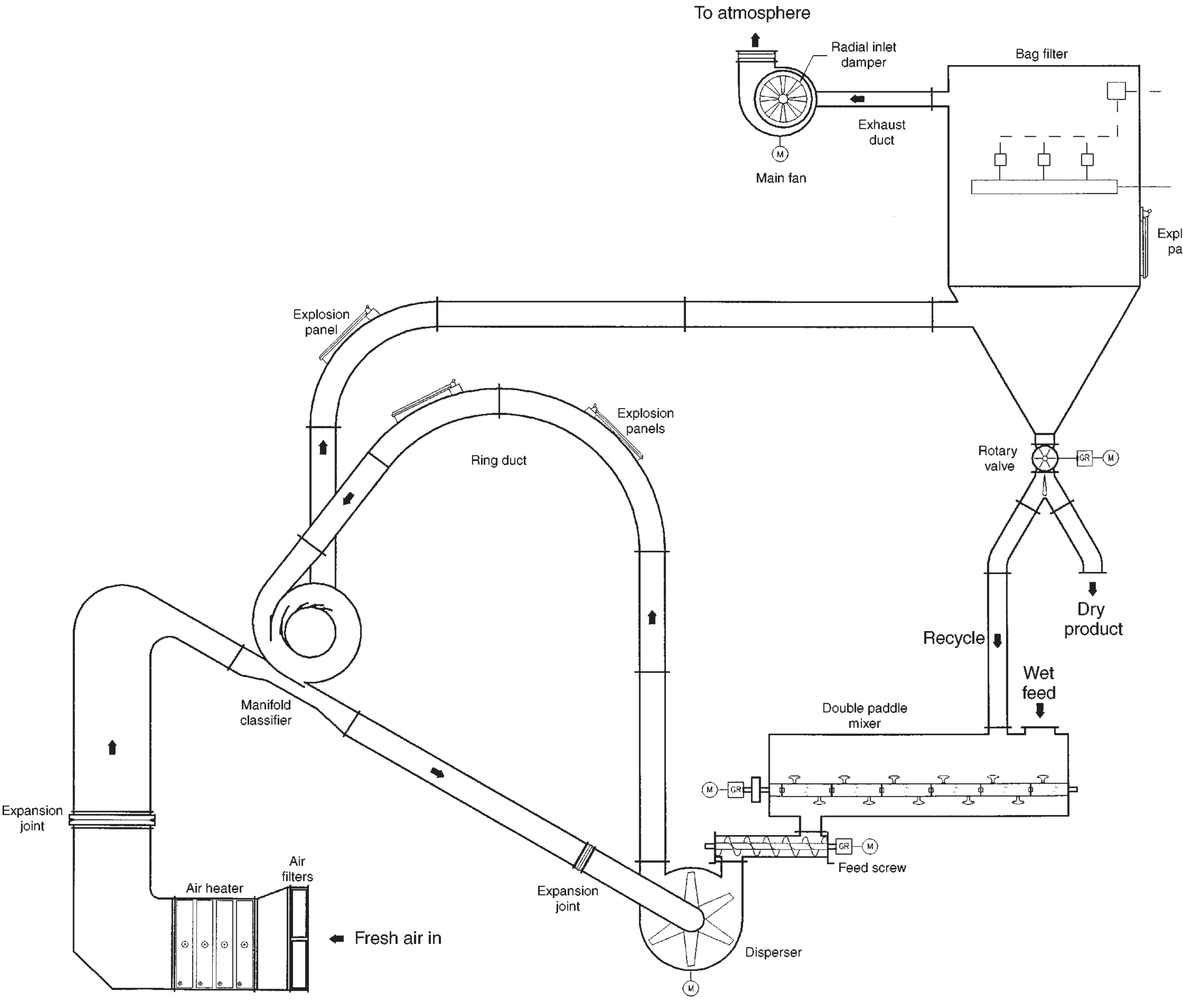


FIG. 12-99 Full manifold-type ring dryer. (*Barr—Rosin*)

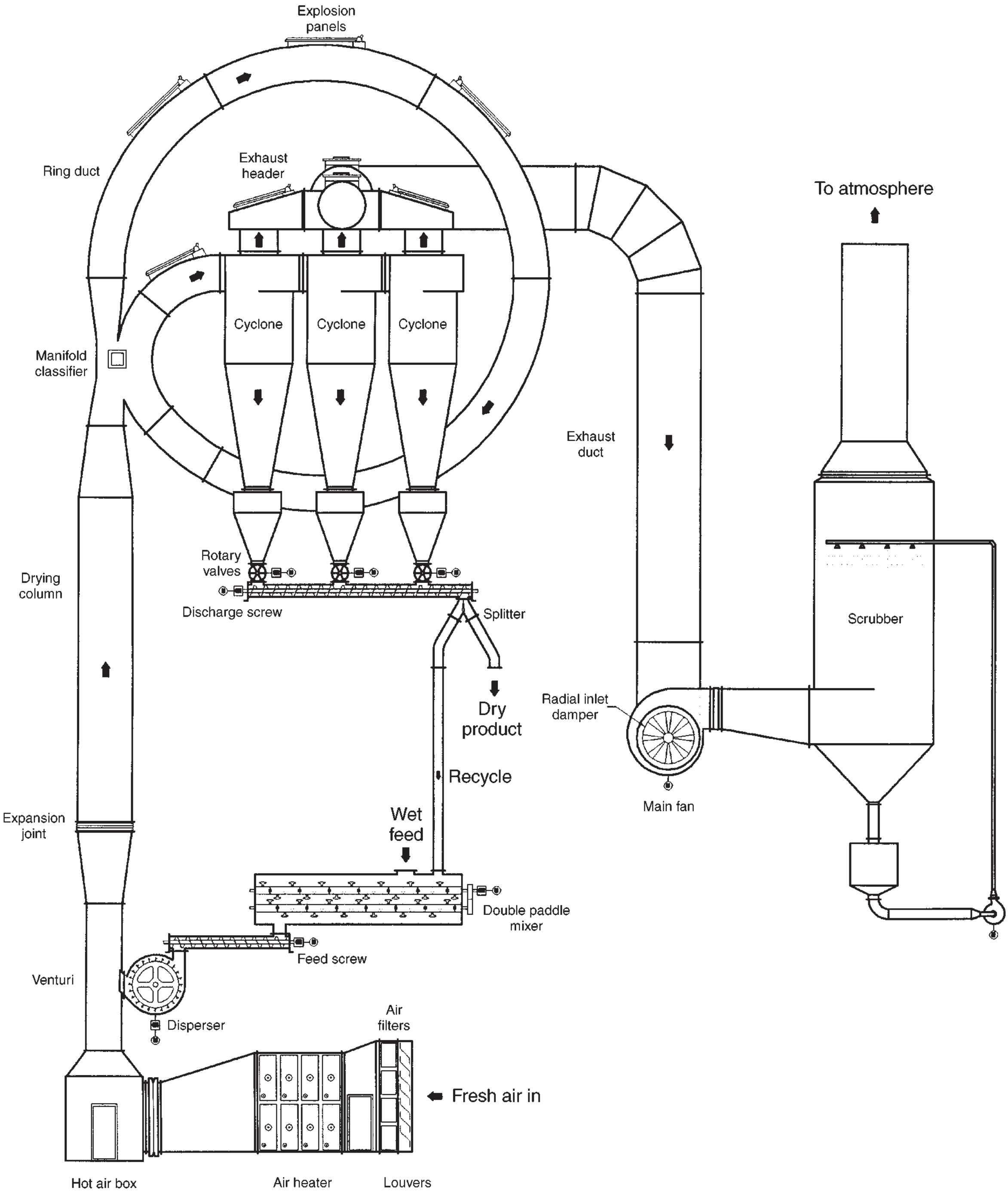


FIG. 12-100 P-type ring dryer. (*Barr—Rosin*)

Special designs of spray dryers may provide for cooling air to enter around the chamber, closed systems for the recovery of solvents, and air sweepers or mechanical rakes to remove dry product from the walls and bottom of the chamber. Some are followed by pneumatic conveyors as depicted in Fig. 12-101, in which drying air is diluted with cool air for product cooling before separation. Spray dryers may operate with cocurrent, mixed, or countercurrent flow of gas and solids. Inlet-gas temperatures may range from 425 to 1100 K.

Pressure nozzles effect atomization by forcing the liquid under high pressure and with a high degree of spin through a small orifice. Pressures may range from 2700 to 69,000 kPa/m^2, depending on the degree of atomization, capacity, and physical properties. Nozzle ori-

TABLE 12-35 Sizes and Capacities of Full Ring Dryers*

Evaporative capacity (lb/hr)	Nominal area in plan (ft × ft)	Nominal height (ft)	Price FOB shops (US$)
1000	7 × 20	20	125,000
2000	10 × 30	24	200,000
5000	12 × 35	28	300,000
10000	18 × 45	32	500,000
15000	20 × 50	35	600,000
20000	22 × 55	38	700,000
40000	25 × 60	40	1,000,000

*Courtesy of Barr—Rosin.

Based upon 1200°F air-inlet temperature. With an inlet temperature of 700°F the evaporative capacity would be half that given in the table. Prices are based upon carbon steel construction with cyclone collector (January, 1995). Motors and secondary dust collectors excluded

fices may range in size from 0.25- to 0.4-mm diameter, depending on the pressure desired for a given capacity and the degree of atomization required. For high pressures and when solids are in suspension in the liquid, the nozzle orifice will be subject to wear by erosion, and the orifice should be made of a hard alloy such as tungsten carbide or stellite. Maintenance on pressure nozzles is always a problem since erosion occurs with even the hardest inserts, and once the orifice has become scratched and nonuniform, good atomization is no longer possible. Likewise, incrustation and plugging by particles of foreign matter cause trouble. Piston pumps furnish the liquids at high pressure; erosion of the valves in these pumps is another maintenance problem.

Spray characteristics of pressure nozzles depend on the pressure and nozzle-orifice size. Pressure affects not only the spray characteristics but also the capacity. If it is desired to reduce the amount of liquid sprayed by lowering the pressure, then the spray may become coarser. To correct this, a smaller orifice would be inserted, which might then require a higher pressure to produce the desired capacity, and a spray that would be finer than desired might result. Multiple nozzles tend to overcome this inflexible characteristic of pressure atomization, although several nozzles on a dryer complicate the chamber design and air-flow pattern and risk collision of particles, resulting in nonuniformity of spray and particle size.

Two-fluid nozzles do not operate efficiently at high capacities and consequently are not used widely on plant-size spray dryers. Their chief advantage is that they operate at relatively low pressure, the liquid being 0 to 400 kPa/m^2 pressure, while the atomizing fluid is usually no more than 700 kPa/m^2 pressure. The atomizing fluid may be steam or air. Two-fluid nozzles have been employed for the dispersion of thick pastes and filter cakes not previously capable of being handled in ordinary atomizers [Baran, *Ind. Eng. Chem.*, **56**(10), 34–36 (1964); and Turba, *Brit. Chem. Eng.*, **9**(7), 457–460 (1964)].

Centrifugal disks atomize liquids by extending them in thin sheets which are discharged at high speeds from the periphery of the rapidly rotating, specially designed disk. The principal objectives in disk design are to ensure bringing the liquid to disk speed and to obtain a uniform drop-size distribution in the atomized liquid. Disk diameters range from 5 cm in small laboratory models to 35 cm for plant-size dryers. Disk speeds range from 3000 to 50,000 r/min. The high speed is generally used in small-diameter dryers. Usual speeds on plant-size dryers range from 4000 to 20,000 r/min, depending on disk diameter and the degree of atomization desired. The degree of atomization as a function of disk speed is affected by the product of disk diameter and speed, i.e., by peripheral speed as opposed to angular speed. Thus, a 13-cm disk operating at 30,000 r/min would be expected to atomize more finely than a 5-cm disk of the same design running at 50,000 r/min.

Centrifugal-disk atomization is particularly advantageous for atomizing suspensions and pastes that erode and plug nozzles. Thick pastes can be handled if positive-pressure pumps are used to feed them to the disk. Disks are capable of operating over a wide range of feed rates and disk speeds without producing too variable a product. Centrifugal disks may be belt-driven, direct-driven by a high-speed electric motor powered by a frequency changer, or driven by a steam turbine. Direct drive by an electric motor has advantages when very high speeds are required and when closely controlled speed variations are necessary. The life of high-speed bearings in centrifugal-disk atomizers depends on the conditions of operation. Average life may be 2000 h. A spare spray machine should be standard equipment.

The particle-size distribution obtained by any one of the three methods of atomization depends on a number of factors. In general, the size distribution will depend on atomizer design, liquid properties, and degree of atomization. If the finest atomization possible is attempted, a limiting condition is approached, and the particle-size range, regardless of the method of atomization, will be narrow. This is particularly true of pressure nozzles, in which uniformity of size increases with pressure. On the other hand, for the production of a coarse product with a high percentage of large particles, the method of atomization will have a large effect on the particle-size distribution. Production of uniform coarse particles from centrifugal disks frequently can be obtained by careful design.

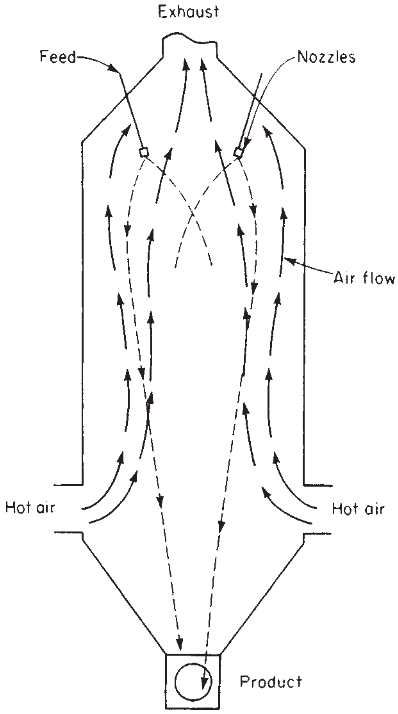
One of the principal advantages of spray drying is the production of a **spherical particle,** which is usually not obtainable by any other drying method. This spherical particle may be solid or hollow, depending on the material, the feed condition, and the drying conditions. In general, aqueous solutions of materials such as soap, gelatin, and water-soluble polymers which form tough tenuous outer skins on drying will form hollow spherical particles when spray-dried. This is attributed to the formation of a casehardened outer surface on the particle which prevents liquid from reaching the surface from the particle interior. Because of high heat-transfer rates to the drops, the liquid at the center of the particle vaporizes, causing the outer shell to expand and form a hollow sphere. Sometimes the rate of vapor generation within the particle is sufficient to blow a hole through the wall of the spherical shell. Spherical particles may be obtained from true solutions or from slurries and may be produced by any of the previously described atomizers.

The physical properties of spray-dried materials are subject to considerable variation, depending on the direction of flow of the inlet gas and its temperature, the degree and uniformity of atomization, the solids content of the feed, the temperature of the feed, and the degree of aeration of the feed. The properties of the product usually of greatest interest are (1) **particle size,** (2) **bulk density,** and (3) **dustiness.** The particle size is a function of atomizer-operating conditions and also of the solids content, liquid viscosity, liquid density, and feed rate. In general, particle size increases with solids content, viscosity, density, and feed rate.

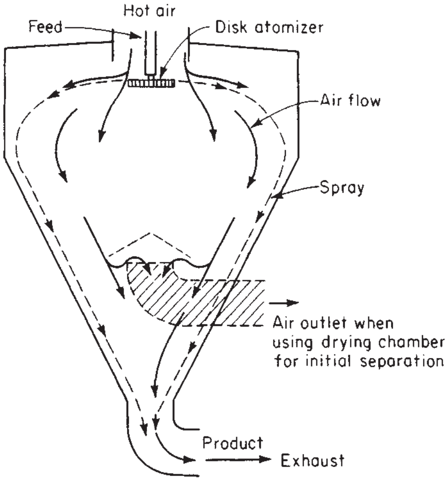
The bulk density of spray-dried solids is frequently the critical property subject to close control. The bulk density of material from a spray dryer may usually be increased by the following operating changes: (1) reducing droplet size, (2) reducing inlet-air temperature, (3) increasing air throughput, (4) increasing air turbulence, (5) employing countercurrent rather than cocurrent gas flow, and (6) effecting a wide range of size distribution from the atomizer. Chaloud et al. evaluated qualitatively the effects of operating variables on the bulk density of particles from detergent spray dryers [*Chem. Eng. Prog.*, **53,** 12, 593–596 (1957)].

A dusty product is caused by fine atomization or particle degradation after drying. Thin-wall hollow particles are susceptible to breakage during collection. Fine atomization and a high gas temperature contribute to high production rates in small drying chambers; they also generate fine particles and thin-wall spheres. Spray-drying installations yielding exceedingly fine and dusty products are often the result of an honest effort to design equipment for maximum capacity at a minimum investment. Large solids particles or heavy-wall spheres require longer drying cycles, hence larger drying chambers. Careful study in the pilot plant is necessary. In commercial installations, classification of particles and separation of a fine fraction from coarse product may be accomplished by countercurrent flow of gas and solids.

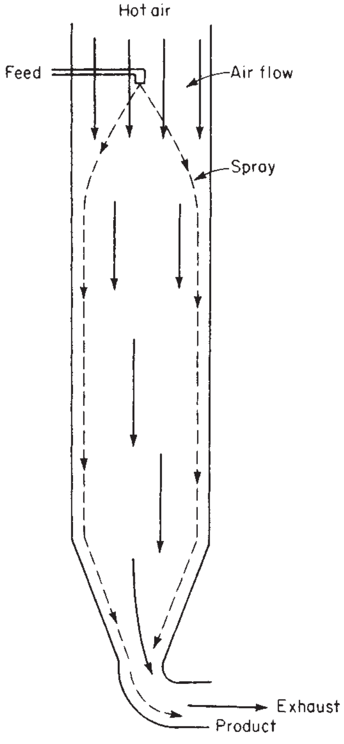
The majority of spray dryers in commercial use employ cocurrent flow of gas and solids. Countercurrent-flow dryers are used primarily for drying soaps and detergents. Their classifying ability is useful in these applications. Air flow is upward, carrying entrained fines from the top of the chamber. The coarse product settles and is removed



(a) Countercurrent



(b) Cocurrent-disk atomization



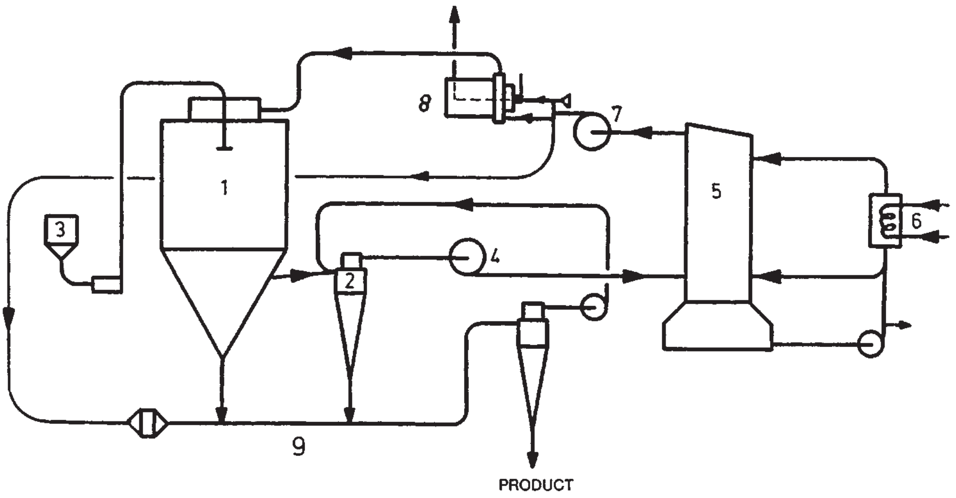
(c) Cocurrent-nozzle atomization

FIG. 12-101 Alternative chambers and gas solids contacting methods in spray dryers.

separately from the bottom of the chamber. Horizontal spray dryers always employ cocurrent flow of gas and solids. A swirling motion is imparted to the air to improve mixing. Many variations of air-flow patterns inside the drying chamber are employed commercially; most are intended primarily to produce turbulence and thorough mixing of gas and droplets and to achieve the most effective use of the chamber volume.

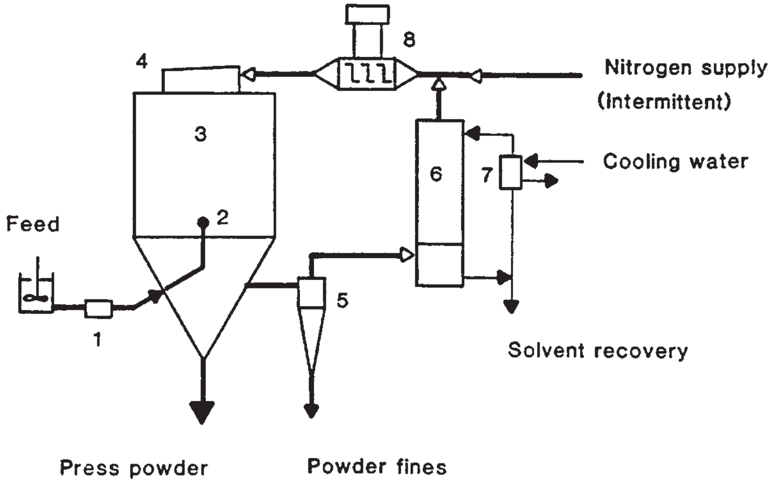
The treatment of drying gas external to the drying chamber may take a variety of forms depending on whether indirect heating (Figs. 12-102 and 103) or direct heating (Figs. 12-104 and 105) is selected; and whether the system is open (Fig. 12-104), semiclosed (Figs. 12-102 and 105), or *totally* closed (Fig. 12-103); and if solvent is flammable, toxic, or total solvent recovery is required.

Applications of Spray Dryers The major and most successful drying applications of spray dryers are for solutions, slurries, and pastes which (1) cannot be dewatered mechanically, (2) are heat-sensitive and cannot be exposed to high-temperature atmospheres for long periods, or (3) contain ultrafine particles which will agglomerate and fuse if dried in other than a dilute condition. In other applications, spray drying is rarely competitive on a cost basis with two-step dewatering and solids-drying processes. The cost of bag collectors for solids recovery from large volumes of exit gas may double the cost of a spray-



1. Drying chamber with atomizer
2. Dry collector
3. Feed system
4. Exhaust fan
5. Scrubber condenser
6. Cooler
7. Supply fan
8. Indirect heater
9. Pneumatic conveying system

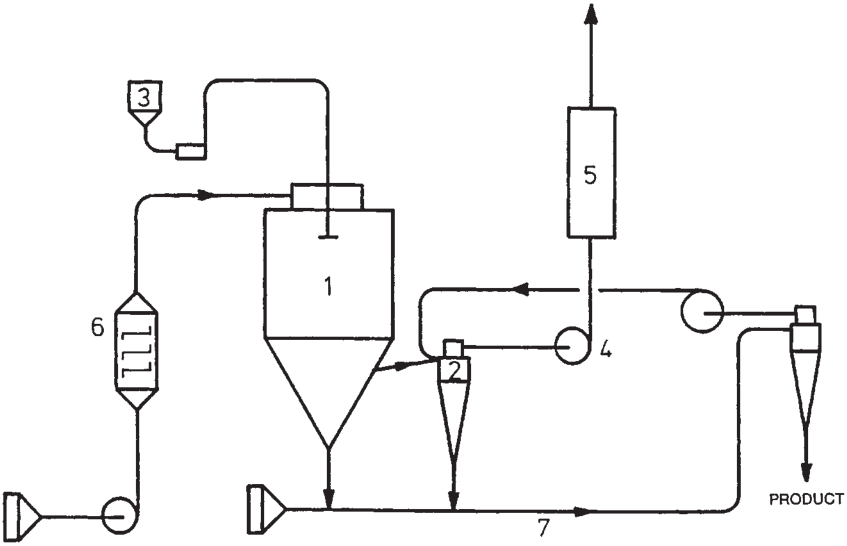
FIG. 12-102 Semiclosed spray-drying cycle with indirect heating. (*NIRO, Inc.*)



1. Feed pump with agitated tanl
2. Nozzle atomizer
3. Drying chamber
4. Gas disperser
5. Cyclone
6. Scrubber condenser
7. Solvent cooler
8. Indirect drying inert gas heater

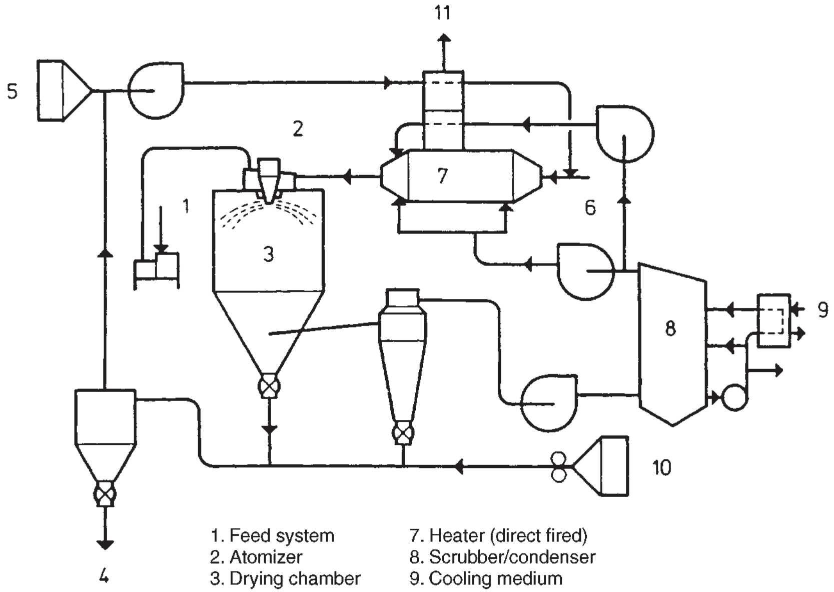
FIG. 12-103 Closed spray-drying cycle with indirect heating. (*NIRO, Inc.*)

dryer installation. Additional costs must usually be justified on the basis of some improvement in product quality, such as particle form, size, flavor, color, or heat stability. Spray drying is applicable to heat-sensitive products such as milk powders and other foods and pharmaceuticals because of the short contact time in the dryer hot zone. Further, the water film on the liquid drop protects the solids from high gas temperatures. Drying is carried out at essentially the drying-air wet-bulb temperature. Color pigments are examples of the class of products for which it is desired to maintain as closely as possible the original solids particle size. Table 12-36 lists typical materials which have been successfully spray-dried. One other class of products particularly applicable to spray dryers is solids slurries, containing extremely fine particles, which is nonnewtonian in flow characteristics and remains fluid at very low moisture content. Certain classes of clays are found in this category. Also, spray dryers have been developed for encapsulation processes to convert liquid volatile flavors and perfumes to particulate solids forms [Maleeny, *Soap Chem. Spec.*, **34,** 1, 135–141 (1958)].



1. Drying chamber with atomizer
2. Dry collector
3. Feed system
4. Exhaust fan
5. Scrubber
6. Heater
7. Pneumatic conveying system

FIG. 12-104 Open spray-drying system with direct-fired heater. (*NIRO, Inc.*)



1. Feed system
2. Atomizer
3. Drying chamber
4. Product outlet
5. Combustion air
6. Fuel burner
7. Heater (direct fired)
8. Scrubber/condenser
9. Cooling medium
10. Conveying air
11. De-activated air bleed

FIG. 12-105 Semiclosed spray-drying cycle with direct heating. (*NIRO, Inc.*)

If the product in no way adheres to the dryer parts and simple cyclone collectors are sufficient for gas-solids separation, batch operation of a spray dryer may be considered. Otherwise, the time and costs for cleaning the large equipment parts make them rarely economical for other than continuous processing of a single material.

Design Methods for Spray Dryers Design variables must be established by experimental tests before final design of a chamber can be carried out. In general, chamber size, atomizer selection, and separation auxiliaries will be determined by the desired physical characteristics of the product. Drying by itself is rarely a problem. An installed spray dryer is relatively inflexible in meeting changing operating requirements while maintaining a constant production rate.

TABLE 12-36 Some Materials That Have Been Successfully Spray-Dried in a 6-m-Diameter by 6-m-High Chamber with a Centrifugal-Disk Atomizer*

Material	Air temperature, K		% water in feed	Evaporation rate, kg/s
	In	Out		
Blood, animal	440	345	65	5.9
Yeast	500	335	86	8.2
Zinc sulfate	600	380	55	10.0
Lignin	475	365	63	6.9
Aluminum hydroxide	590	325	93	19.4
Silica gel	590	350	95	16.9
Magnesium carbonate	590	320	92	18.2
Tanning extract	440	340	46	5.2
Coffee extract	420	355	70	3.8
Detergent *A*	505	395	50	5.0
Detergent *B*	510	390	63	6.2
Detergent *C*	505	395	40	2.6
Manganese sulfate	590	415	50	5.5
Aluminum sulfate	415	350	70	1.7
Urea resin *A*	535	355	60	3.8
Urea resin *B*	505	360	70	1.9
Sodium sulfide	500	340	50	2.0
Pigment	515	335	73	13.2

*Courtesy of NIRO, Inc.

NOTE: The fan on this dryer handles about 5.2 m³/s at outlet conditions. The outlet-air temperature includes cold air in-leakage, and the true temperature drop caused by evaporation must therefore be estimated from a heat balance.

Important variables which must be fixed before design of a commercial dryer are the following:

1. The form and particle size of product required
2. The physical properties of the feed: moisture, viscosity, density, etc.
3. The maximum inlet-gas and product temperatures

Theoretical correlations of spray-dryer performance published by Gluckert [*Am. Inst. Chem. Eng. J.*, **8**(4), 460–466 (1962)] may be employed for the scale-up of laboratory dryers and, in some instances, for estimating dryer requirements in the absence of any tests.

Several assumptions are necessary.

1. The largest droplets, which dry most slowly, are the limiting portion of the spray. They determine ultimate chamber dimensions and are employed for the evaluation.
2. The largest droplet in a spray population is 3 times the diameter of the average drop size [see Eq. (12-66)].
3. A droplet Nusselt number = 2, corresponding to pure conduction (Reynolds number = 0) to infinity, is employed for evaluating the coefficient of heat transfer.
4. Drying conditions, because of turbulence and gas mixing, are uniform throughout the chamber; i.e., the entire chamber is at the gas exit temperature—this fact has been well established in many chambers except in the immediate zone of gas inlet and spray atomization.
5. The temperature driving force for drying is the difference between the drying-gas outlet temperature and, in the case of pure water, the gas wet-bulb temperature. In the case of a solution, the adiabatic saturation temperature of the pure saturated solution is employed rather than the wet-bulb temperature.

Methods for calculating average and maximum drop sizes from various atomizers are given by Marshall (op. cit.). For pneumatic nozzles, an expression developed by Nukiyama and Tanasawa is recommended:

$$\bar{X}_{vs} = \frac{1920\sqrt{\alpha}}{V_a\sqrt{\rho_l}} + 597\left(\frac{\mu}{\sqrt{\alpha\rho_l}}\right)^{0.45}\left(\frac{1000Q_L}{Q_a}\right)^{1.5} \qquad (12\text{-}63)$$

where $\bar{X}_{vs}$ = average drop diameter, μm (a drop with the same volume-surface ratio as the total sum of all drops formed)
α = surface tension, dyn/cm
μ = liquid viscosity, P
V_a = relative velocity between air and liquid, ft/s
ρ_l = liquid density, g/cm³
Q_L = liquid volumetric flow rate
Q_a = air volumetric flow rate

For single-fluid pressure nozzles, a rule of thumb is employed:

$$\bar{X}_{vs} = 500/\sqrt[3]{\Delta P} \qquad (12\text{-}64)$$

where ΔP = pressure drop across nozzle, lb/in².

For centrifugal disks, the relation of Friedman, Gluckert, and Marshall is employed [*Chem. Eng. Prog.*, **48,** 181 (1952)]:

$$\frac{D_{vs}}{r} = 0.4\left(\frac{\Gamma}{\rho_l N r^2}\right)^{0.6}\left(\frac{\mu}{\Gamma}\right)^{0.2}\left(\frac{\alpha\rho_l L_w}{\Gamma^2}\right)^{0.1} \qquad (12\text{-}65)$$

where D_{vs} = average drop diameter, ft
r = disk radius, ft
Γ = spray mass velocity, lb/(min·ft of wetted disk periphery)
ρ_l = liquid density, lb/ft³
N = disk speed, r/min
μ = liquid viscosity, lb/(ft·min)
α = surface tension, lb/min²
L_w = wetted disk periphery, ft

NOTE: All groups are dimensionless. To convert dynes per square centimeter to joules per square meter, multiply by 10^{-3}; to convert poises to newton-seconds per square meter, multiply by 10^{-1}; to convert feet per second to meters per second, multiply by 0.3048; to convert feet to meters, multiply by 0.3048; to convert pounds per minute-foot to kilograms per second-meter, multiply by 0.025; to convert pounds per cubic foot to kilograms per cubic meter, multiply by 16.019; to convert pounds per minute squared to kilograms per second squared, multiply by 1.26×10^{-4}; to convert British thermal units per hour to kilojoules per second, multiply by 2.63×10^{-4}; and to convert British thermal units per hour-square foot-degree Fahrenheit per foot to joules per square meter-second-kelvin per meter, multiply by 1.7307.

Inspection of these relationships will show that the variables are difficult to specify in the absence of tests except when handling pure liquids—which in spray drying is rare indeed. The most useful method for employing these equations is to conduct small-scale drying tests in a chamber under conditions in which wall impingement and sticking are incipient. The maximum particle size can then be back-calculated by using the relationships given in the following paragraphs, and the effects of changing atomizing variables evaluated by using the preceding equations:

$$\bar{X}_m = 3\bar{X}_{vs} \qquad (12\text{-}66)$$

where $\bar{X}_m$ = maximum drop diameter, μm.

Gluckert gives the following relationships for calculating heat transfer under various conditions of atomization:

Two-fluid pneumatic nozzles:

$$Q = \frac{6.38K_f v^{2/3}\,\Delta t}{D_m^2}\,\frac{w_s}{\rho_s}\sqrt{\frac{\rho_a}{w_a V_a}\,\frac{w_a + w_s}{w_a}} \qquad (12\text{-}67)$$

Single-fluid pressure nozzles:

$$Q = \frac{10.98K_f v^{2/3}\,\Delta t}{D_m^2}\,D_s\sqrt{\frac{\rho_t}{\rho_s}} \qquad (12\text{-}68)$$

Centrifugal-disk atomizers:

$$Q = \frac{4.19K_f (R_c - r/2)^2\,\Delta t}{D_m^2\rho_s}\sqrt{\frac{w_s\rho_t}{rN}} \qquad (12\text{-}69)$$

where Q = rate of heat transfer to spray, Btu/h
K_f = thermal conductivity of gas film surrounding the droplet, Btu/(h·ft²)(°F·ft), evaluated at the average between dryer gas and drop temperature
v = volume of dryer chamber, ft³
Δt = temperature driving force (under terminal conditions described above), °F
D_m = maximum drop diameter, ft
w_s = weight rate of liquid flow, lb/h
ρ_s = density of liquid, lb/ft³

w_a = weight rate of atomizing air flow, lb/h
ρ_a = density of atomizing air, lb/ft^3
V_a = velocity of atomizing air at atomizer, ft/h
D_s = diameter of pressure-nozzle discharge orifice, ft
ρ_t = density of dryer gas at exit conditions, lb/ft^3
R_c = radius of drying chamber with centrifugal disk, ft
r = radius of disk, ft
N = rate of disk rotation, r/h

For proper use of the equations, the chamber shape must conform to the spray pattern. With cocurrent gas-spray flow, the angle of spread of single-fluid pressure nozzles and two-fluid pneumatic nozzles is such that wall impingement will occur at a distance approximately four chamber diameters below the nozzle; therefore, chambers employing these atomizers should have vertical height-to-diameter ratios of at least 4 and, more usually, 5. The discharge cone below the vertical portion should have a slope of at least 60°, to minimize settling accumulations, and is used entirely to accelerate gas and solids for entry into the exit duct.

The critical dimension of a centrifugal-disk chamber is the diameter. Vertical height is usually 0.5 to 1.0 times the diameter; the large cone is needed mainly to accelerate to the discharge duct and prevent settling; it contributes little to drying capacity.

Cost Data for Spray Dryers Drying chambers, ductwork, and cyclone separators are usually constructed of stainless steel. Savings of roughly 20 percent may be achieved on the total purchase cost by using carbon steel; the increasing tendency toward the use of heat-resistant and corrosion-resistant plastic coatings (epoxy resins) makes the future appear promising for greater use of carbon steel construction. Wide differences in cost may be experienced in the selection of basic equipment. Air heaters vary in price range according to the selection of steam, electricity, direct-fired, and indirect-fired oil or gas heaters. Dust-collection equipment may consist of cyclone collectors or bag-type filters and may include a wet scrubber. Costs of nozzle and centrifugal atomizers are usually comparable. While the centrifugal atomizer requires mechanical gearing and motor drive, a high-pressure nozzle requires a high-pressure pump, which will usually more than offset the cost of gearing and motor for the centrifugal atomizer. Auxiliary equipment which may be included comprises air filters, drying-chamber insulation, and mechanical or pneumatic cooling conveyors. A minimum of instrumentation consists of indicating and recording thermometers for inlet-air and outlet temperatures, an ammeter for atomizer motor drive (or a pressure gauge for nozzle atomization), a flowmeter, manometers, a high-temperature alarm, and a panelboard with push-button stations for all equipment. The drying process may be completely controlled automatically with some additional instrumentation.

Spray dryers may operate under positive, negative, or neutral pressures. In general, pressure drop in a complete system will range from 15 to 50 cm of water, depending on duct size and separation equipment employed.

Agitated Flash Dryers Agitated flash dryers produce fine powders from feeds with high solids contents, in the form of filter cakes, pastes, or thick, viscous liquids. Many continuous dryers are unable to dry highly viscous feeds. Spray dryers require a pumpable feed. Conventional flash dryers often require backmixing dry product to the feed in order to fluidize. Other drying methods for viscous pastes and filter cakes are well known, such as contact, drum, band and tray dryers. They all require long processing time, large floor space, high maintenance, and after treatment such as milling.

The agitated flash dryer offers a number of process advantages: such as ability to dry pastes, sludges, and filter cakes to a homogeneous, fine powder in a single-unit operation; continuous operation; compact layout; effective heat and mass transfer—short drying times; negligible heat loss—high thermal efficiency; and easy access and cleanability.

The agitated flash dryer (Fig. 12-106) consists of four major components: feed system, drying chamber, heater, and exhaust air system.

Wet feed enters the feed tank which has a slow-rotating impeller to break up large particles. The level in the feed tank is maintained by a level controller. The feed is metered at a constant rate into the drying chamber via a screw conveyor mounted under the feed tank. If the feed is shear thinning and can be pumped, the screw feeder can be replaced by a positive-displacement pump.

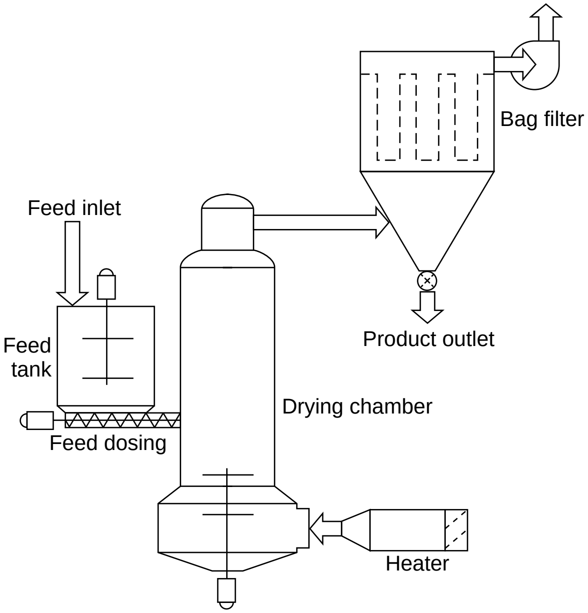


FIG. 12-106 Agitated flash dryer with open cycle. (*NIRO, Inc.*)

The drying chamber is the heart of the system consisting of three important components: air disperser, rotating disintegrator, and drying section. Hot, drying air enters the air disperser tangentially and is introduced into the drying chamber as a swirling airflow. The swirling airflow is established by a guide-vane arrangement. The rotating disintegrator is mounted at the base of the drying chamber. The feed, exposed to the hot, swirling airflow and the agitation of the rotating disintegrator, is broken up and dried. The fine dry particles exit with the exhaust air and are collected in the bag filter. The speed of the rotating disintegrator controls the particles' size. The outlet air temperature controls the product-moisture content.

The drying air is heated either directly or indirectly, depending upon the feed material, powder properties, and available fuel source. The heat sensitivity of the product determines the drying air temperature. The highest possible value is used to optimize thermal efficiency. A bag filter is usually recommended for collecting the fine particles produced. The exhaust fan maintains a slight vacuum in the dryer, to prevent powder leakage into the surroundings. The appropriate process system is selected according to the feed and powder characteristics, available heating source, energy utilization, and operational health and safety requirements.

Open systems use atmospheric air for drying. In cases where products pose a potential for dust explosion, plants are provided with pressure relief or suppression systems. For recycle systems, the drying system medium is recycled and the evaporated solvent recovered as condensate. There are two alternative designs: Self-inertizing mode, where oxygen content is held below 5 percent by combustion control at the heater. This is recommended for products with serious dust-explosion hazards; Inert mode, where nitrogen is the drying gas. This is used when an organic solvent is evaporated or product oxidation during drying must be prevented.

Design Methods The size of the agitated flash dryer is based on the evaporation rate required. The operating temperatures are product-specific. Once established, they determine the airflow requirements. The drying chamber is designed based on air velocity (approximately 3–4 m/s) and residence time (product-specific).