

Drying of Solid Materials

See also Solids Technology, Introduction

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Symbols

A	surface area of the drying solid, m^2
C	excess air factor in Eq. (38)
C	radiation coefficient, $\text{W m}^{-2} \text{K}^{-4}$
c	specific heat, $\text{J kg}^{-1} \text{K}^{-1}$
d	particle diameter, m
h	enthalpy, J/kg
L	dryer length, m
l	modified mean free path, m
M	mass, kg
\dot{M}	mass flow rate, kg/s
\tilde{M}	molecular mass, kg/kmol
\dot{m}	drying rate, $\text{kg m}^{-2} \text{s}^{-1}$
N	number of moles, kmol
P	pressure, Pa
\dot{Q}	heat transfer rate, W
\dot{q}	heat flux, W/m^2

R	gas constant, $\text{J kg}^{-1} \text{K}^{-1}$
s	width of sample, m
T	temperature, K
t	time, s
u	velocity of drying agent, m/s
v	velocity of liquid in capillaries, m/s
\dot{W}	power, W
X	moisture content in solid, kg moisture/kg dry solid
\tilde{x}	mole fraction in the liquid phase
Y	humidity of the drying agent, kg moisture/kg drying agent
\tilde{y}	mole fraction in the gas phase
z	axial coordinate in a dryer, m
z	distance from the free surface of sample, m
α	heat-transfer coefficient, $\text{W m}^{-2} \text{K}^{-1}$

β	mass-transfer coefficient, m/s
γ	accommodation coefficient
δ	diffusion coefficient, m^2/s
δ	surface roughness, m
ζ	dimensionless axial coordinate in a dryer
Λ	mean free path, m
λ	thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
μ	ratio of molecular masses
$\dot{\nu}$	normalized drying rate, Eq. (23)
ξ	normalized moisture content, Eq. (24)
ρ	density, kg/m^3
τ	dimensionless time
Φ	dimensionless number, Eq. (29)
φ	relative humidity
φ	surface coverage
ψ	porosity

Subscripts

a	ambient
bed	bed
crit	at the critical point
eq	in equilibrium
f	final, at the outlet
g	gas (drying agent)
h	maximum hygroscopic moisture content
heat	from the heater
i	initial, at the inlet
l	liquid (moisture)
lost	heat losses to the surroundings
max	maximum
p	at constant pressure
r	radiation
s	dry solid
v	vapor
vent	ventilator
W	wall
w	wetting
l	component index (isopropyl alcohol)
I	in the first period of drying

Superscripts

0	effective coefficient, Eqs. (15), (17)
*	saturated
\sim	molar quantities

1. Theoretical Fundamentals of the Drying Process

1.1. Concepts, Definitions

Drying denotes the separation of volatile liquids from solid materials by vaporizing the liquid and removing the vapor. The liquid that is to be removed is usually water, but it could also be a solvent such as alcohol or acetone, or a mixture of such solvents. The solid material that is to be dried can be a natural product such as wood, a semifinished or a finished good (such as paper). The removal of water from other fluids such as refrigerants or from gases, such as natural gas, is also considered a drying process, but this topic is not treated in this article.

The vaporization of liquids requires the supply of heat. Accordingly, drying can be considered a *thermal separation process*. The removal of liquids from solids without the application of heat, which is the case in a centrifuge, does not come under the strict definition of drying.

The product that is to be dried is denoted as the moist solid, or simply as the solid. The substance that carries the necessary heat is called the drying agent. This substance could be air, an inert gas, or superheated steam. Heat could also be supplied by radiation, by hot surfaces, or by microwaves. The moisture content of the solid is denoted by X and measured in kg liquid per kg of dry solid. For the humidity of a gaseous drying agent the symbol Y is used (in kg vapor per kg of dry gas). The saturation humidity is denoted by Y^* . The mass flux of the vapor leaving the surface of the solid per unit time is called the drying rate, and is denoted by the symbol \dot{m} (in $\text{kg m}^{-2} \text{s}^{-1}$). The drying rate is usually determined by measuring the change of moisture content with time dX/dt . It follows that

$$\dot{m} = - \frac{M_s}{A} \frac{dX}{dt}$$

M_s is the mass of the dry solid, and A is the portion of its surface area that is in contact with the drying agent. The drying rate \dot{m} depends on the conditions of drying and on the moisture content X . The drying conditions are specified by factors such as the air pressure, temperature, and humidity, the radiator temperature, the temperature of a heating surface, or the strength of the microwaves. The relationship of the drying rate

\dot{m} and the moisture content X under constant drying conditions – this is $\dot{m}(X)$ – is called the *drying rate curve*.

1.2. Characteristics of Moist Solids

Almost all industrial products have to be dried one or more times in the course of their manufacture. Consequently, the variety and characteristics of moist solids are manifold. However, only two of these characteristics have a direct influence on the drying rate curve $\dot{m}(X)$. They relate to the questions:

- 1) Is the liquid in the solid freely mobile or is it bonded to the solid by sorption?
- 2) Does vaporization take place at the surface or in the interior of the solid?

The first characteristic is described by the thermodynamic equilibrium (sorption isotherms), the second by the kinetics of liquid migration in the interior of the solid (capillarity, diffusion). Both topics will be treated thoroughly subsequently. In any case it should be borne in mind that drying is not only a thermal separation process; it is also a means to manufacture specified products and to influence their quality. Paper is an example of such a specified product whose quality is controlled by the choice of drying conditions. Further, the risk of possible product damage during drying must be reduced. This is particularly important for sensitive products such as foodstuffs. In this context, a large number of product characteristics differing from material to material should be accounted for. Some remarks on the handling of temperature-sensitive materials are given in Section 3.1

Free and Bonded Moisture in Solids. If free (unbound) liquid is in contact with its own vapor, then the vapor pressure is equal to the saturation pressure for the respective temperature $P_{v*}(T)$, e.g., $P_{v*} = 0.1$ MPa for water at 100°C . In the presence of an inert gas (e.g., air), the total pressure at the surface of the liquid P is equal to the sum of the saturation pressure P_{v*} and of the partial pressure of the inert gas P_g :

$$P = P_v^*(T) + P_g \quad (1)$$

In most practical cases the total pressure P is prescribed. The partial pressure of the inert gas can be obtained from Eq (1):

$$P_g = P - P_v^*(T) \quad (2)$$

The ratio of the partial pressure to the total pressure is equal to the mole fraction of the respective component. It follows:

$$\tilde{y}_v^*(T) = \frac{N_v}{N_v + N_g} = \frac{P_v^*}{P} \quad (3)$$

and correspondingly

$$\tilde{y}_g = \frac{N_g}{N_v + N_g} = \frac{P_g}{P} \quad (4)$$

The number of moles N (expressed in kmol), is related to the mass of the respective component M (expressed in kg) by the molecular mass \tilde{M} (which is given in kg/kmol) by

$$M_v = N_v \tilde{M}_v \quad M_g = N_g \tilde{M}_g \quad (5a,b)$$

($\tilde{M}_v = 18.01$ kg/kmol for water and $\tilde{M}_g = 28.96$ kg/kmol for air) From Eqs. (1)–(5) the saturation humidity of the inert gas [$Y^*(T)$ in kg vapor per kg inert gas] can be obtained:

$$Y^*(T) = \frac{\tilde{M}_v}{\tilde{M}_g} \frac{P_v^*(T)}{P - P_v^*(T)} \quad (6)$$

The humidity of the unsaturated inert gas is given by the relationship

$$Y = \frac{\tilde{M}_v}{\tilde{M}_g} \frac{\varphi P_v^*(T)}{P - \varphi P_v^*(T)} \quad (7)$$

where φ is the relative humidity, defined as

$$\varphi = P_v / P_v^*(T) \quad (8)$$

The limits of φ are 0 and 1, which correspond to completely dry air and vapor-saturated air, respectively. In summary, the thermodynamic equilibrium between the unbound moisture within a solid that is in contact with a gas–vapor atmosphere is characterized by $\varphi = 1$ and $Y = Y^*(T)$. This is the case regardless of the magnitude of the moisture content X .

If the moisture is bonded (bound) to the solid material, the air humidity under conditions of thermodynamic equilibrium (denoted by Y_{eq}) depends not only on the temperature T , but also on the moisture content X_{eq} , i.e., $Y_{eq} = Y_{eq}(T, X_{eq})$. The parameter Y_{eq} is always

smaller than Y^* and consequently, the partial vapor pressure in the gas – vapor mixture $P_{v,eq}$ is always smaller than the saturation vapor pressure $P_{v^*}(T)$. The diminishing of the vapor pressure at the surface of materials with a high moisture content is associated with the phenomenon called *capillary condensation*. With a low moisture content (down to the limit $X \rightarrow 0$), the intermolecular attraction between the fluid and the solid plays a dominant role. One speaks of *Langmuir sorption*. For practical purposes the equilibrium moisture content of a solid X_{eq} is depicted as a function of the relative humidity of the air φ at various temperatures T , i.e., $X_{eq} = X_{eq}(\varphi, T)$. Such curves are called *sorption isotherms* (Fig. 1).

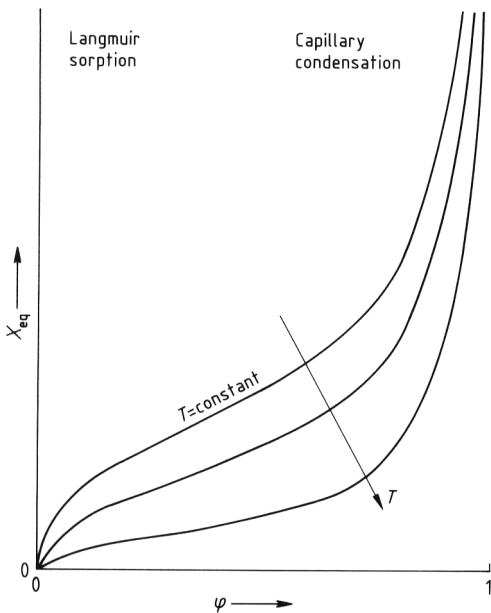


Figure 1. Sorption isotherms $X_{eq}(\varphi, T)$ (qualitative graph)

Figure 2 shows two sorption isotherms for potatoes. To dry potatoes to a residual moisture content of $X_{eq} = 0.10$, for example, cold air with a temperature of $T = 0^\circ\text{C}$ and a low relative humidity of $\varphi = 0.24$, or hot air with a temperature of 100°C and a high relative humidity of $\varphi = 0.77$ could be used.

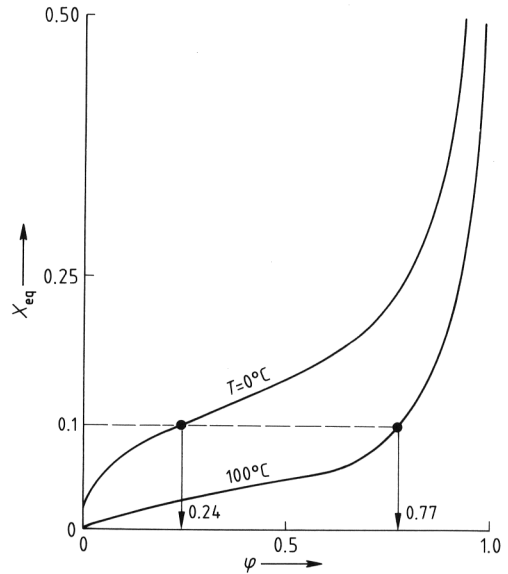


Figure 2. Sorption isotherms for potatoes [1]

Sorption isotherms also aid in choosing the drying conditions when using steam as the drying agent. Taking the potatoes as an example, if the steam temperature is 100°C , then its pressure should not exceed 77 kPa in order to attain a residual moisture of $X_{eq} = 0.10$.

Solids that contain a considerable amount of bonded moisture at normal conditions are usually called hygroscopic. Sorption isotherms for many such solids are to be found in [1]; some are presented in Figure 3.

Figure 3. Sorption isotherms for various materials [1]

A) Cereal foods and tobacco

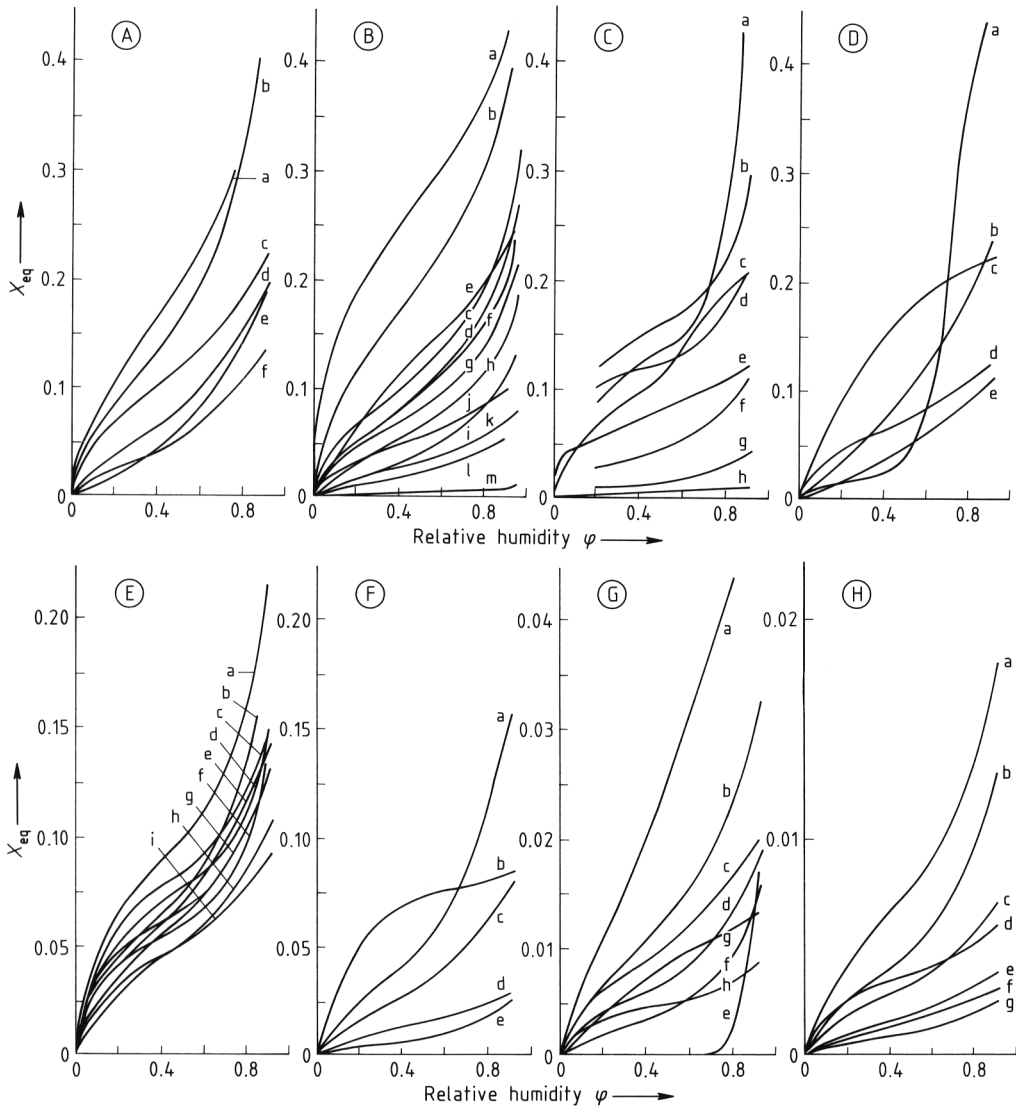
a) Tobacco leaves; b) Tobacco; c) Macaroni; d) Flour; e) Bread; f) Crackers

B) Textile fibers

a) Beryllium alginate fiber (25°C); b) Calcium alginate fiber (25°C); c) Nitrate fiber (25°C), copper fiber (25°C), viscose fiber (25°C), wool (worsted, 25°C); d) Casein fiber (20°C), wool (35.6°C); e) Jute; f) Cotton (mercerized, 20°C), silk; g) Flax (30°C), hemp; h) Cotton, fluffed (20°C); i) Acetate fiber (25°C); j) Linen; k) Perlon fiber (25°C), nylon fiber (25°C); l) Cellulose acetate fiber; m) Pe-Ce fiber (20°C)

C) Leather, rubber, catgut, feathers

a) Sheepskin; b) Leather (sole, oak tanned); c) Catgut; d) Gold beater skin; e) Feathers; f) Latex dipped cord; g) Reclaimed rubber; h) Rubber



Liquids that are bound to solids by sorption are in a state of lower free energy than those that are unbound. Hence, in the drying of hygroscopic substances, the enthalpy of wetting Δh_w must be included in addition to the vaporization enthalpy Δh_v . The so-called differential heat of wetting can be calculated from the relationship

$$\Delta h_w = -R_v \left[\frac{d \ln \varphi}{d (1/T)} \right]_{X_{eq} = \text{constant}} \quad (9)$$

where R_v is the gas constant of the vapor. When the logarithm of the relative humidity is plotted versus the reciprocal value of the absolute temperature at constant equilibrium moisture content, straight lines are obtained (*sorption isosteres*). The sorption isosteres and the differential heat of wetting for potatoes are plotted in Figures 4 and 5, respectively. To calculate the amount of heat needed to accomplish drying to a final moisture content $X_{eq, f}$ from an initial moisture content $X_{eq, i}$, the integral heat of wetting is needed.

$$\overline{\Delta h_w} = \frac{1}{X_{eq, i} - X_{eq, f}} \int_{X_{eq, f}}^{X_{eq, i}} \Delta h_w dX_{eq} \quad (10)$$

The total enthalpy change Δh_{total} is the sum of the vaporization enthalpy and the integral enthalpy of wetting:

$$\Delta h_{total} = \Delta h_v + \overline{\Delta h_w} \quad (11)$$

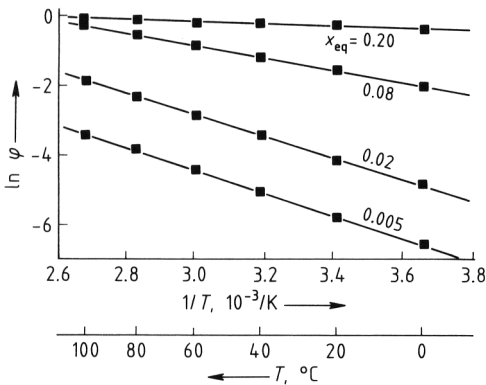


Figure 4. Sorption isosteres for potatoes
The graph can be used for the determination of the differential heat of wetting.

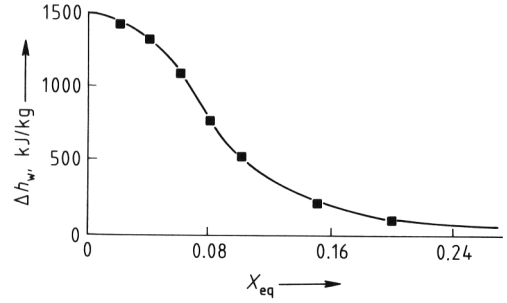


Figure 5. Differential heat of wetting Δh_w for potatoes as a function of their equilibrium moisture content X_{eq} [1]
The points for $X_{eq} = 0.20, 0.08$, and 0.02 can be calculated from the slope of the corresponding straight lines in Figure 4, according to Eq. (9).

1.3. Drying Rate Curves for Convection Drying

In most cases, drying rate curves are experimentally determined using air as the drying agent. During each experiment of this kind the air conditions, that is the total pressure P , the temperature T , the relative humidity φ , and the air velocity u are kept constant (Fig. 6). The sample is weighed at specified intervals of time Δt , the reduction of mass ΔM is calculated ($\Delta M = M_s \Delta X$), and the drying rate is obtained:

$$\dot{m} = - \frac{1}{A} \frac{\Delta M}{\Delta t} = - \frac{M_s}{A} \frac{\Delta X}{\Delta t} \quad (12)$$

For most moist solids, especially those having capillary porosity, the drying rate \dot{m} depends upon the moisture content X in a manner similar to that shown in Figure 7 [1], [2].

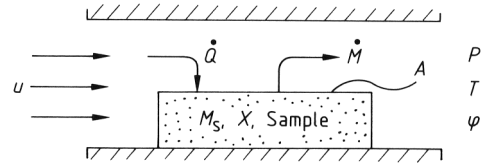


Figure 6. Schematic of a drying tunnel to measure the drying rate curve

In the first drying period, the drying rate remains practically constant. During this period, unbound liquid is vaporized from the surface of the solid and carried away by the drying agent. When the moisture content is reduced below a critical value X_{crit} , the surface of the solid dries out, and further evaporation takes place in the

interior of the porous solid. The drying rate decreases with decreasing moisture content. This is called the second drying period. The residual moisture in the solid is bound to it by sorption. The drying rate decreases rapidly with decreasing moisture content and tends to zero as the hygroscopic equilibrium moisture content $X_{eq}(T, \varphi)$ is approached. The regime between the maximum hygroscopic moisture content X_h and the equilibrium value of X_{eq} is designated as the third drying period.

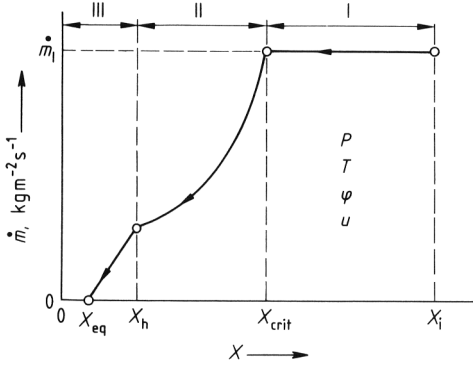


Figure 7. Typical drying rate curve $\dot{m}(X)$, showing the first, second, and third period of drying

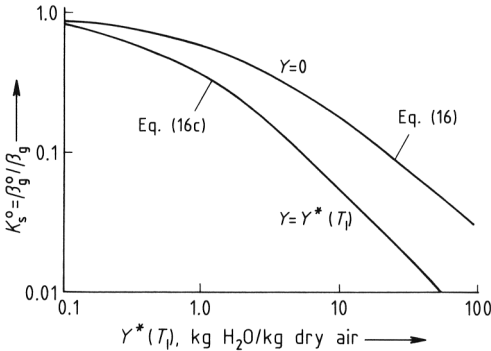


Figure 8. Stefan correction K_s^0 as a function of the saturation humidity $Y^*(T_1)$ for the limiting cases $Y=0$ and $Y=Y^*(T_1)$. Curves are calculated for water vapor and air, $\mu = 1.608$.

First Drying Period. The drying rate during the first period (denoted by \dot{m}_I) is dependent only upon the conditions of drying and not upon the characteristics of the solid: there is only evaporation from the surface of the solid. The temperature of the solid, denoted by T_I , is established so that the heat flux from the drying agent to the

solid \dot{q} is equal to the product of the drying rate and the vaporization enthalpy,

$$\dot{q} = \dot{m}_I \Delta h_v \quad (13)$$

The drying agent, usually air, is completely saturated at the surface of the solid,

$$Y \text{ (at the surface of the solid)} = Y^*(T_I) \quad (14)$$

Assuming that the humidity in the bulk of the drying agent is equal to Y , where $Y < Y^*(T_I)$, the drying rate \dot{m}_I is proportional to the humidity difference $Y^*(T_I) - Y$. The proportionality constant is the effective mass-transfer coefficient β_g^0 . Hence,

$$\dot{m}_I = \rho_g \beta_g^0 [Y^*(T_I) - Y] \quad (15)$$

In this expression ρ_g is the density of air (or other drying agent). The coefficient β_g^0 is related to the real mass-transfer coefficient β_g by

$$\beta_g^0 = \beta_g \frac{\ln \frac{1 + \mu Y^*(T_I)}{1 + \mu Y}}{\mu [Y^*(T_I) - Y]} \quad (16)$$

in which

$$\mu = \tilde{M}_g / \tilde{M}_v \quad (16a)$$

is the ratio of the molecular masses of the inert gas and the vapor ($\mu = 28.96/18.01 = 1.606$ for air and water vapor). For low levels of humidity ($Y < Y^*(T_I) < 0.05$), Equation 16 reduces to

$$\beta_g^0 = \beta_g \quad (16b)$$

For the case $Y \rightarrow Y^*(T_I)$,

$$\beta_g^0 = \beta_g \frac{1}{1 + \mu Y^*(T_I)} \quad (16c)$$

is obtained. The effective mass-transfer coefficient β_g^0 is always smaller than the real one β_g . Only at sufficiently low humidities Y are the two coefficients equal. This fact is illustrated in Figure 8, where the dependence of the so-called *Stefan correction* $K_s^0 = \beta_g^0 / \beta_g$ on the saturation humidity is depicted.

The saturation humidity $Y^*(T_I)$ can be found from the energy balance given by Equation 13, where the heat flux \dot{q} is given by

$$\dot{q} = \alpha^0 (T - T_I) \quad (17)$$

In this equation T_I is the solid temperature during the first drying period, T is the temperature

in the bulk of the drying agent, and α^0 is the effective heat-transfer coefficient. The latter is related to the real heat-transfer coefficient α by the following relationship:

$$\alpha^0 = \alpha \cdot \frac{\Delta h_v}{c_{pv}(T - T_I)} \ln \left[1 + \frac{c_{pv}(T - T_I)}{\Delta h_v} \right] \quad (18)$$

In this equation Δh_v is the vaporization enthalpy of the liquid and c_{pv} is the heat capacity of the vapor. The value of α^0 is smaller than the value of α . If the temperature difference $(T - T_I)$ is sufficiently small, these two heat-transfer coefficients are practically the same. Figure 9 shows the relationship between $\alpha^0/\alpha = K_A$ and $c_{pv}(T - T_I)/\Delta h_v$. The former is sometimes called the *Ackermann correction*, while the latter is termed the *phase change number*.

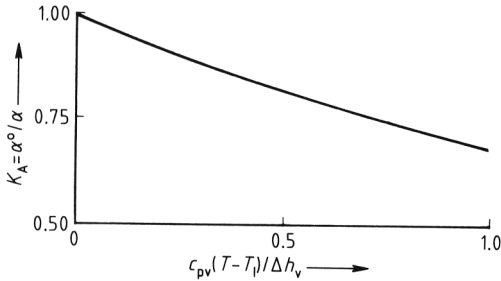


Figure 9. Ackermann correction K_A as a function of the phase change number $c_{pv}(T - T_I)/\Delta h_v$

The temperature that the solid reaches in the first drying period T_I can be found by inserting the equation for the mass transfer (Eq. 15) and the equation for the heat transfer (Eq. 17) into the energy balance (Eq. 13). The result is

$$\alpha^0 (T - T_I) = \rho_g \beta_g^0 [Y^*(T_I) - Y] \Delta h_v \quad (19)$$

For solids wetted by water that are to be dried by air, the approximation

$$\frac{\alpha^0}{\beta_g^0} \frac{1}{\rho_g} \approx c_{pg} + Y c_{pv} \quad (20)$$

is useful provided that the saturation humidity $Y^*(T_I)$ is not too high. The quantities c_{pg} and c_{pv} are the heat capacities of air and water vapor, respectively. Whenever Equation (20) is valid, Equation (19) can be transformed into one that is written in the coordinates of the Mollier diagram:

$$\frac{h^*(T_I) - h}{Y^*(T_I) - Y} = c_{pl} T_I \quad (21)$$

In this relationship c_{pl} is the heat capacity of the liquid and h is the enthalpy of the moist air

$$h = c_{pg} T + Y (\Delta h_v^0 + c_{pv} T) \quad (22)$$

where Δh_v^0 is the vaporization enthalpy at 0 °C. Equation (21) is the locus of points of the *adiabatic saturation line*, crossing the curve with $\varphi = 1$ at the point (h^*, Y^*) (Fig. 10).

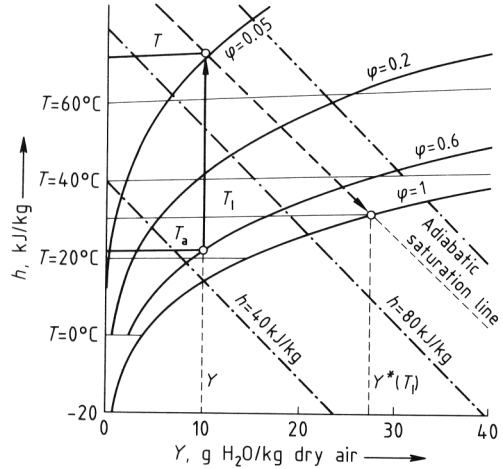


Figure 10. Mollier diagram for moist air
Evaluation of the solid's temperature T_I in the first period of drying

If the temperature of the solid T_I and either the heat-transfer coefficient α^0 or the mass-transfer coefficient β_g^0 are known, then the drying rate can be determined numerically either with Equations (17) and (13) or with Equation (15).

Numerical Example. Consider the drying agent to be ambient air ($T_a = 22^\circ\text{C}$, $\varphi = 0.60$) that has been heated to $T = 72^\circ\text{C}$. The heat-transfer coefficient at the air–solid interface is $20 \text{ W m}^{-2} \text{ K}^{-1}$ ($= \alpha^0$), the moisture is water. What is the drying rate during the first drying period?

The temperature of the solid during the first drying period T_I can be evaluated with the help of the Mollier diagram (Fig. 10). Condition of ambient air: $T_a = 22^\circ\text{C}$, $\varphi = 0.60 \Rightarrow Y = 0.010 \text{ kg H}_2\text{O/kg dry air}$. Condition of pre-heated air: $T = 72^\circ\text{C}$, $Y = 0.010 \text{ kg H}_2\text{O/kg dry air} \Rightarrow \varphi = 0.05$. Following the adiabatic saturation line, a value of $T_I = 30^\circ\text{C}$ is obtained. The

corresponding vaporization enthalpy of water is $\Delta h_v = 2\,430\,300 \text{ J/kg}$ (tabulated value). Using Equations (13) and (17), the drying rate during the first drying period $\dot{m}_1 = 1.24 \text{ kg m}^{-2} \text{ h}^{-1}$ is obtained.

Second and Third Drying Periods. The first drying period is completed when the solid's moisture content X has reached the critical value X_{crit} (cf. Fig. 7). After this point the capillary forces are no longer sufficient to transport the liquid to the surface of the solid. The liquid–vapor interface (drying front) moves inside the solid. The dried portion of the solid near the surface thermally insulates the moist inner portions of the solid. At the same time these dried regions impede the transport of the vapor to the bulk of the drying agent. These are the reasons why the drying rate decreases while the solid's temperature rises after the completion of the first drying period. The critical moisture content X_{crit} must usually be determined experimentally; Table 1 gives representative values for various materials.

Table 1. Critical moisture content of solids when dried in air [3]

Solid	Layer thickness, cm	Critical moisture content X_{crit}
Sulfite pulp	0.6–1.9	0.6–0.8
Paper, white eggshell	0.02	0.41
Paper, fine book	0.0125	0.33
Paper, coated	0.01	0.34
Paper, newsprint		0.6–0.7
Beaverboard	0.43	>1.2
Poplar wood	0.42	1.2
Wool fabric, worsted		0.31
Wool, undyed serge		0.08
Sole leather	0.63	>0.9
Chrome leather	0.1	1.26
Sand (50–150 mesh)	5	0.05
Sand (200–325 mesh)	5	0.1
Sand (through 325 mesh)	5	0.21
Sea sand (on trays)	0.63	0.03
	1.27	0.047
	2.5	0.059
	5.0	0.06
Brick clay	1.6	0.14
Kaolin		0.14
Barium nitrate (crystals)	2.5	0.07
Carbon pigment	1	0.4
Copper carbonate	2.5–3.8	0.6
Iron blue pigment	0.63–1.9	1.1
Lithopone press cake	0.63	0.064
	1.27	0.08
	1.9	0.12
	2.5	0.16
Prussian blue pigment		0.4
Gelatin ($X_i = 4.0$)	0.25–0.5 (moist)	3.0
White lead		0.11
Rock salt	2.5	0.07

In Figure 11, measurements of the moisture content within a paper sample during drying are depicted. The width of the sample was $s = 30 \text{ mm}$, its depth – measured from the surface which is in contact with the drying agent – is denoted by z . After 7 or 8 h, drying is still taking place in the first drying period. The surface of the sample is moist, the moisture content is almost evenly distributed over the entire depth of the sample. About 9 h after the beginning of the experiment, the critical point is reached. The surface of the sample dries out and the second drying period begins. After 65 or 95 h, drying takes place in the third drying period. All moisture is bonded, the drying rate is very small. The drying rate curve, associated with the experiment in Figure 11 is depicted in Figure 12 (curve d). Additionally, three other curves for thinner samples are shown. The thinner samples dry more rapidly in the second and third drying periods than the thicker ones.

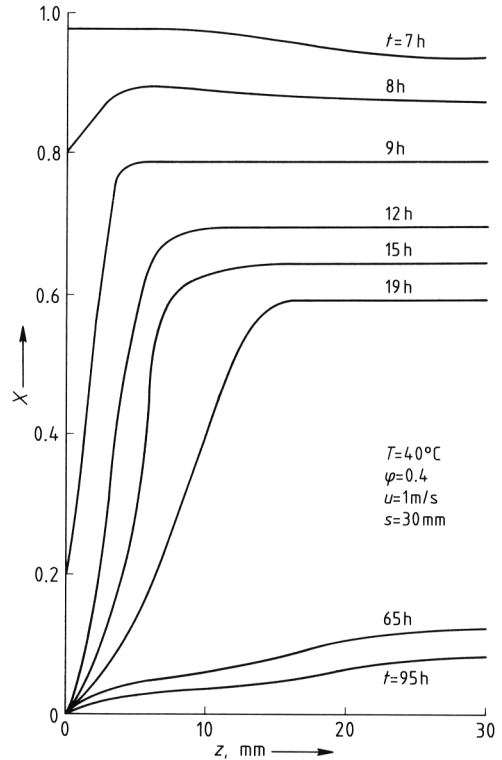


Figure 11. Moisture profile in paper stock as a function of the duration of drying [1]

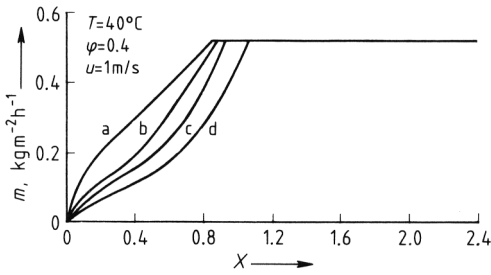


Figure 12. Drying rate curves for paper stock of various thicknesses [1]
Sample thickness s in mm a) 10; b) 15; c) 20; d) 30

The history of the temperature at various positions within a layer of powder is presented in Figure 13. In the first drying period the entire sample takes on the temperature T_I that can be read from a Mollier diagram. This temperature

is usually referred to as the adiabatic saturation temperature. In the second and third drying periods, the temperature rises continuously in the various internal layers of the solid with the result that they approach the temperature of the drying agent. Large differences in moisture content and temperature can occur in the solid after the first drying period has been completed. Such differences can produce fissures in the solid, as well as scaling and discoloration.

Drying rate curves $\dot{m}(X)$ are usually determined experimentally. If the process is sufficiently slow, the sample can be periodically weighed. In rapid processes, such as the drying of paper by a transverse flow of air, which is completed in a matter of a few seconds, the humidity of the exhaust air can be determined continuously with an infrared spectrometer. Figure 14

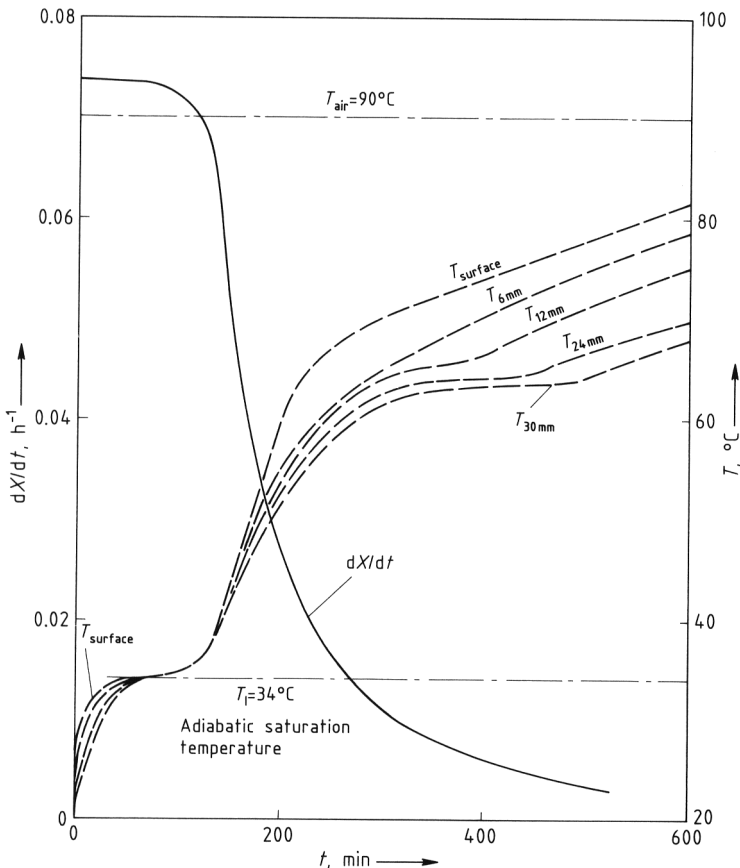


Figure 13. Drying rate curve and temperatures at various depths of the sample during the drying of powdered CaCO_3 [1]

shows drying rate curves that were obtained in this way for a textile fabric through which air was blown [4].

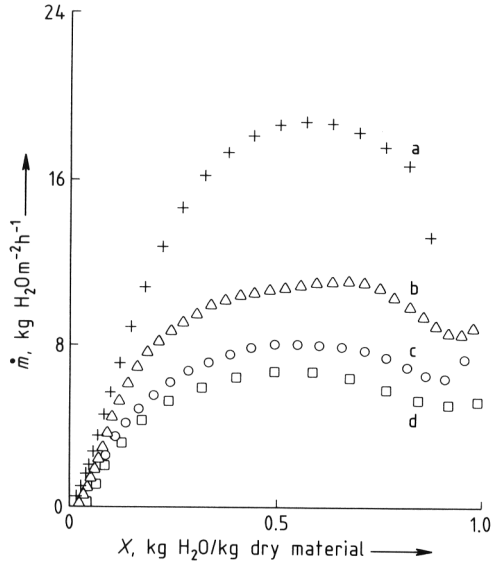


Figure 14. Drying rate curves for a textile fabric dried by passing air through it [4]
a) $T=71.7^\circ\text{C}$; b) $T=39.4^\circ\text{C}$; c) $T=25.3^\circ\text{C}$;
d) $T=22.8^\circ\text{C}$

As already discussed, drying rate curves are obtained from laboratory tests that are conducted under constant drying agent conditions. In reality, the condition of the drying agent changes with time and location in any commercial drying apparatus. Because it is seldom possible to simulate all of the conditions that can occur in a production dryer, methods of interpolating the laboratory data are needed. In this context, the use of a drying rate curve is very helpful. The normalized drying rate is defined by

$$\dot{\nu} = \dot{m} / \dot{m}_I \quad (23)$$

and the normalized moisture content by

$$\xi = \frac{X - X_{eq}}{X_{crit} - X_{eq}} \quad (24)$$

When $\dot{\nu}$ is plotted versus ξ , most drying rate curves measured in air under different conditions coincide (Figs. 15 and 16). In such cases, only one drying rate curve has to be determined by experiment.

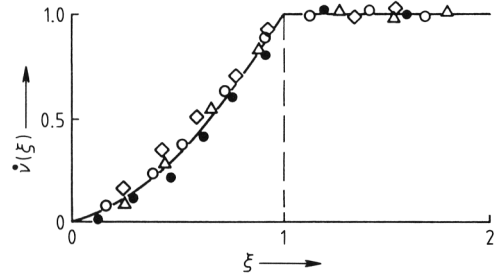


Figure 15. Normalized drying rate curve for pottery clay
The air temperature T and the relative humidity φ were varied [1]:

○ $T=45^\circ\text{C}$, $\varphi=0.537$; △ $T=15^\circ\text{C}$, $\varphi=0.537$
● $T=25^\circ\text{C}$, $\varphi=0.187$; ◇ $T=25^\circ\text{C}$, $\varphi=0.758$

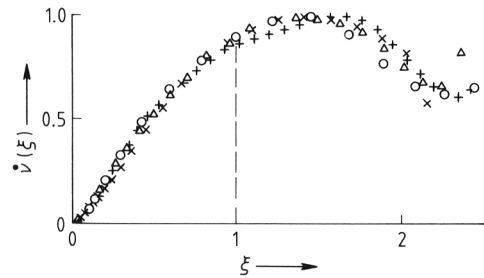


Figure 16. Normalized drying rate curve calculated from the data of Figure 14

× $T=71.7^\circ\text{C}$; + $T=39.4^\circ\text{C}$; △ $T=25.3^\circ\text{C}$; ○ $T=22.8^\circ\text{C}$

1.4. Drying Rate Curves for Contact Drying

In contact drying the heat necessary to vaporize the moisture in the solid is transferred by direct contact with a heated surface. The process of drying can take place in an atmosphere containing only the liquid's vapor, or air can also be present. Vacuum dryers are an example of the former, tube dryers for peat an example of the latter. Figure 17 shows a laboratory tray dryer equipped with an agitator. The entire experimental setup is placed on a balance and can be used in order to measure drying rate curves of porous, granular materials in vacuum. During each experiment the temperature of the heating surface T_w and the chamber pressure P are held constant. The same apparatus can be used in order to measure drying rate curves in the presence of inert gas.

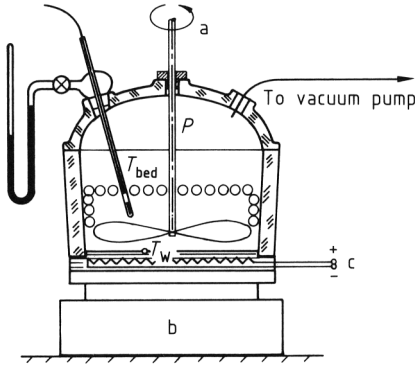


Figure 17. Laboratory tray dryer to determine the drying rate during contact drying
a) Mixer; b) Balance; c) Heater

The drying rate curves shown in Figure 18 were obtained with the apparatus of Figure 17 during vacuum contact drying of moist granular aluminum silicate; the particle diameter d was varied. Figure 19 gives similar results for peat in the presence of air (at normal pressure). In both cases, the drying rate depends upon the efficiency of the heat transfer between the heating surface and the granular bed, as well as upon the intensity of mechanical mixing. The reduction of the drying rate with decreasing moisture content is a consequence of the increased blocking of the heating surface by the particles that have already been dried. Consequently, the drying rate curve appears to be a property of the agitated bed as a whole, and not of the individual porous particles.

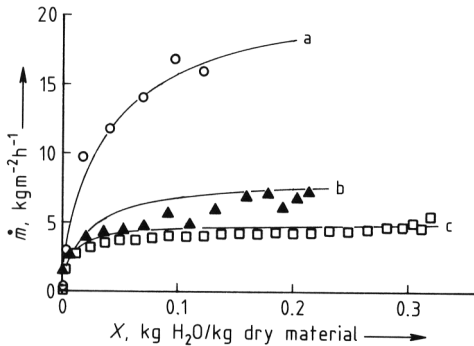


Figure 18. Drying rate curves for nonhygroscopic, vacuum-dried aluminum silicate particles
Conditions: $P = 2.63 \text{ kPa}$, $T_w = 80^\circ\text{C}$, and mixer speed = 45 rpm
a) $d = 0.83 \text{ mm}$; b) $d = 3.25 \text{ mm}$; c) $d = 6.60 \text{ mm}$

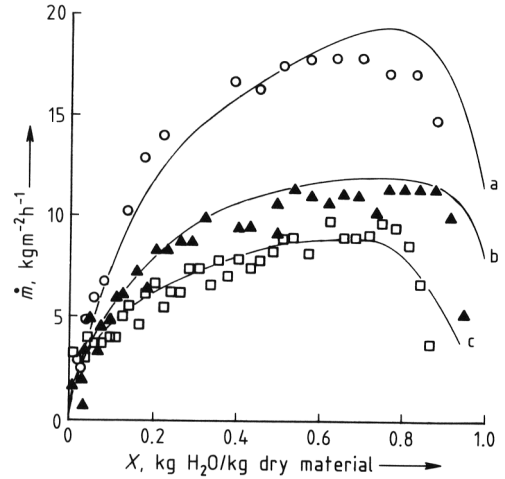


Figure 19. Drying rate curves for hygroscopic peat in the tray dryer of Figure 17
Conditions: $P = 0.1 \text{ MPa}$ (air), $T_w = 130^\circ\text{C}$, and mixer speed = 40 rpm
a) $d = 0.75 \text{ mm}$; b) $d = 3.0 \text{ mm}$; c) $d = 6.0 \text{ mm}$

Contact drying becomes faster as the temperature difference between the heated wall and the bed ($T_w - T_{bed}$) increases or the mixing speed is raised. For coarse-grained materials ($d \approx 10 \text{ mm}$), the drying rate is directly proportional to the temperature difference, for fine materials ($d \approx 100 \mu\text{m}$) it depends approximately upon the square root of this difference $(T_w - T_{bed})^{0.5}$. In contrast, the mixing intensity has a stronger influence on the drying rate of fine-grained materials than on the drying rate of coarse-grained ones. The physical explanation for this behavior can be found in [5]. The maximum drying rate that can be expected is given by

$$\dot{m}_{\max} = \alpha_{\max} (T_w - T_{bed}) / \Delta h_v \quad (25)$$

The maximum possible heat-transfer coefficient, α_{\max} , can be found from

$$\alpha_{\max} = \alpha_r + \varphi_w \frac{4\lambda}{d} \left[\left(1 + \frac{2(l+\delta)}{d} \right) \ln \left(1 + \frac{d}{2(l+\delta)} \right) - 1 \right] \quad (26)$$

with

$$l = 2A \left(\frac{2}{\gamma} - 1 \right) \quad (27)$$

and

$$\alpha_r = 4C_{w,bed} \left(\frac{T_w + T_{bed}}{2} \right)^3 \quad (28)$$

λ	molecular thermal conductivity of vapor or inert gas
d	mean particle diameter
δ	surface roughness of the particles (in most cases $0 < \delta < 10 \mu\text{m}$ [5], [6])
φ_w	fraction of the heated surface that is covered ($\varphi_w \approx 0.8$ for random beds of spherical particles)
Λ	mean free path of the vapor or inert gas molecules
γ	accommodation coefficient ($\gamma \approx 0.9$ for air or water vapor at moderate temperatures)
$C_{w, \text{bed}}$	coefficient for thermal radiation between the heated surface and the bed

The radiant heat-transfer coefficient α_r has a value of approximately $5 \text{ W m}^{-2} \text{ K}^{-1}$ at room temperature. For high vacuum, the molecular conduction, the second term in Equation (26), is insignificant so that $\alpha_{\text{max}} = \alpha_r$ is obtained. If this limit is reached, the drying rate can only be increased if the temperature difference ($T_w - T_{\text{bed}}$) is made larger; in this instance, the degree of mixing has no effect on the drying process.

1.5. Drying Rate and Moisture-Composition Curves for Solids Wetted by Liquid Mixtures

A large variety of solids are moistened with liquid mixtures containing water and other substances such as alcohol, acids, or esters. In the course of drying such solids, the composition of the moisture generally changes because different liquids evaporate at different rates. This is termed *selective drying*, to denote the preferential removal of individual components from the mixture. However, under certain circumstances the composition of the moisture remains constant during drying (*unselective drying*). The properties of the dried item are often very strongly dependent upon the composition of the residual moisture. Moreover, there are accepted industry and health standards that the final moisture content must meet. Pharmaceutical items must not contain any toxic residues; food-stuffs should be dried to remove their water but not their (highly volatile) aromas. Although lacquers should dry with a constant composition, no fixed rules can be given because the requirements in individual cases differ.

The drying rate as well as the selectivity of the drying process are controlled by five inter-related physical mechanisms:

Phase equilibrium between the gaseous, liquid, and solid phases

Diffusion in the gaseous phase

Diffusion in the liquid phase

Capillary transport of moisture

Heat transfer

The combined influence of these five mechanisms on selectivity of drying has been theoretically and experimentally examined using simple liquid mixtures [7], [8]. According to the results of such investigations, the influence of vapor–liquid equilibria and gas-phase diffusion on the one hand, and the influence of capillary transport and liquid-phase diffusion on the other hand act together.

Furthermore, it is necessary to differentiate between liquid mixtures containing only volatile components and those containing at least one nonvolatile component. A mixture of alcohol, water, and glycerol is an example of the second kind. In all drying processes with a sufficiently high drying rate and a large thickness of the solid (large samples, coarse-grained products), the selectivity is determined by the capillary motion and the diffusion of the liquid constituents. This is the case when the dimensionless number

$$\Phi_1 = \frac{\delta_1}{v(d/2)} \quad (29)$$

is considerably greater than unity. This parameter is equal to the ratio of two lengths: the penetration depth of the concentration profile, $\varepsilon = \delta_1/v_1$, and the depth of the sample, $d/2$. The velocity of the capillary flow v_1 is directly proportional to the drying rate \dot{m} , i.e., $v_1 = \dot{m}/(\varrho_1 \cdot \psi)$. (Note: ϱ_1 is the density of the liquid phase, δ_1 is the diffusion coefficient in this phase, and ψ is the porosity of the sample.) If the solution within the pores of the solid contains only volatile components, such as water, alcohol, or acetone, then for $\Phi_1 \ll 1$ “sharp” drying proceeds unselectively (in sharp drying the drying agent has a high temperature, and the drying rate is high). But should the liquid in the pores contain one or more nonvolatile components, then the volatile component that diffuses most quickly through the nonvolatile constituent of the mixture disappears preferentially. An example is the water in a solution with glycerol and alcohol. The relative volatility of the individual components, as well

as the speed of diffusion into the gaseous drying agent, is inconsequential in this case. This situation is important because of the possibility of suppressing the loss of aroma during drying of foodstuffs.

If the dimensionless number Φ_1 is considerably larger than unity (low temperature of drying agent, low drying rate), then the selectivity is solely determined by the relative volatility and by the velocity of diffusion into the gaseous phase. The more volatile components disappear first, as long as “dynamic azeotropy” does not occur. The appearance of such azeotropic points is due to the interaction of relative volatility and gaseous diffusion. For the solution of isopropyl alcohol and water, the (static) azeotropic mole fraction of isopropyl alcohol is about 0.65. However, using dry air as drying agent a dynamic azeotropic mole fraction of 0.41 can be attained; the reason for this behavior is that water diffuses into the air much faster than alcohol. At this composition the drying process would be unselective for all values of the parameter Φ_1 .

Figures 20 and 21 clarify the drying behavior of solids that are wetted by solutions with only volatile components. The experimental drying rate and composition curves for a clay cylinder are shown in Figure 20. The clay has been soaked in a solution of isopropyl alcohol and water. The drying agent is dry air ($T = 60^\circ\text{C}$, $u = 0.2\text{ m/s}$).

Because of the relatively large diameter of the sample, the parameter Φ_1 remains much lower than unity during the first drying period. Consequently, the process is controlled by the diffusion in the liquid phase. In the absence of an inert liquid component the drying process occurs unselectively, i.e., the mole fraction of the alcohol, \tilde{x}_1 , remains constant, as illustrated in Figure 20B. This situation changes in the course of the second drying period: with decreasing moisture content, the liquid–vapor interface retreats inside the solid, so that the drying rate and the width of the moist region diminish. The result is that Φ_1 increases. Towards the end of the drying process a pronounced change in the composition of the remaining moisture is recorded. The extent and trend of this selectivity are dictated by the diffusion occurring in the gaseous phase, and by the thermodynamic equilibrium. For an initial mole fraction of alcohol $\tilde{x}_{1,i} > 0.41$, the criterion for dynamic azeotropy, the solution becomes depleted of water, and for $\tilde{x}_{1,i} < 0.41$, alcohol is lost.

The region of selective drying can be considerably extended if the thickness of the sample is decreased. In this manner, the drying of a thin-walled hollow cylinder made of sintered bronze with dry air ($T = 60^\circ\text{C}$ and $v = 0.2\text{ m/s}$), occurs selectively from the beginning (see Fig. 21).

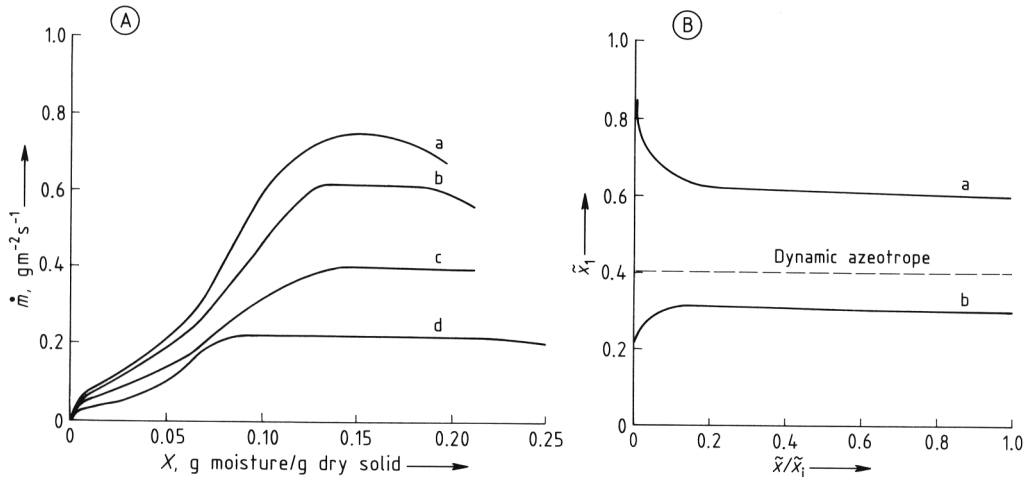


Figure 20. Drying rate (A) and composition curves (B) for a clay cylinder wetted by isopropyl alcohol ('1') and water. Conditions: diameter of sample = 39.2 mm, length = 95.7 mm; drying agent: dry air, $T = 60^\circ\text{C}$, $u = 0.2\text{ m/s}$ [7].
 A) a) $\tilde{x}_{1,i} = 1.0$; b) $\tilde{x}_{1,i} = 0.6$; c) $\tilde{x}_{1,i} = 0.3$; d) $\tilde{x}_{1,i} = 0.0$
 B) a) $\tilde{x}_{1,i} = 0.6$; b) $\tilde{x}_{1,i} = 0.3$

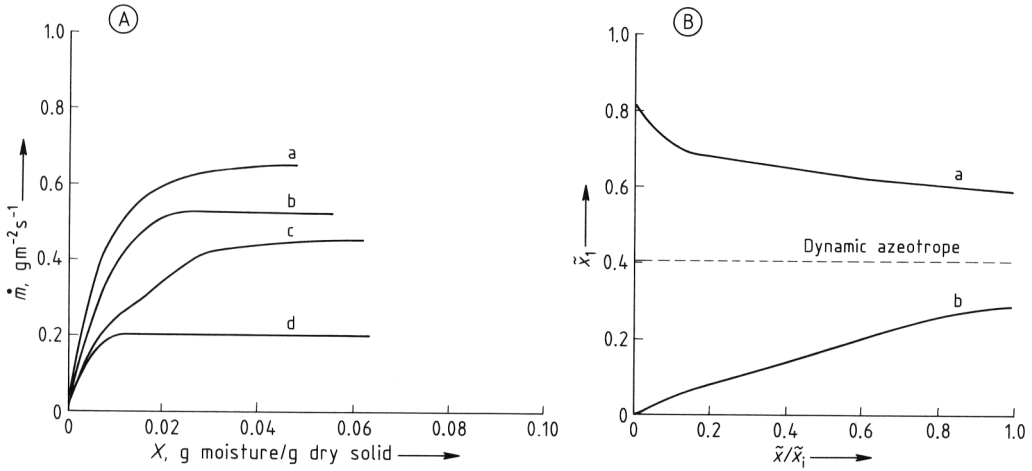


Figure 21. Drying rate (A) and composition curves (B) for a hollow cylinder of sintered bronze wetted by isopropyl alcohol ('1') and water

Conditions: outer diameter of sample = 31.0 mm; inner diameter of sample = 30.0 mm; length = 95.7 mm; drying agent: dry air, $T = 60^\circ\text{C}$ and $u = 0.2\text{ m/s}$ [7]

A) a) $\tilde{x}_{1,i} = 1.0$; b) $\tilde{x}_{1,i} = 0.6$; c) $\tilde{x}_{1,i} = 0.3$; d) $\tilde{x}_{1,i} = 0.0$

B) a) $\tilde{x}_{1,i} = 0.6$; b) $\tilde{x}_{1,i} = 0.3$

2. Drying Methods and Dryer Types

In this chapter the most important methods of drying are arranged according to the way the heat is transferred. In a convection dryer the liquid is vaporized by the heat that is transferred from the drying agent. In the case of a contact dryer the heat is conducted from a heated surface to the solid. The solid may be transported over the heat-transfer surface, or it may rest upon it. Radiant heating, in which the heat is supplied from a radiation source that is remote from the surface of the solid but with an unobstructed view of it, is also used. Special methods of drying include dielectric drying and freeze drying. The myriad of dryer types is a consequence of the different behavior that the solid exhibits during drying, the particular product needs, and many economic considerations.

2.1. Convection Drying

The methods of convection drying differ from one another in the manner by which the moist solid contacts the drying agent, which is usually hot air.

2.1.1. Flowing Gas

Drying with a flowing gas is particularly suitable for materials which should not be mechanically stressed during drying.

Drying Oven (Kiln). With small quantities of moist solids, the simplest, cheapest dryer is a drying oven similar to that shown in Figure 22.

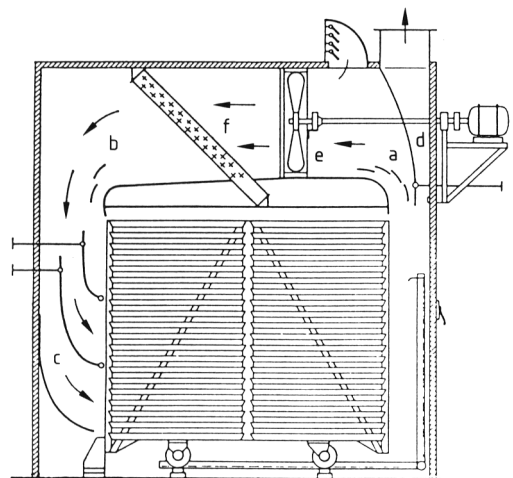


Figure 22. Compartment dryer (Courtesy of Babcock BSH)
a)–c) Turning vanes; d) Air-exhaust duct with damper; e) Fan; f) Heaters

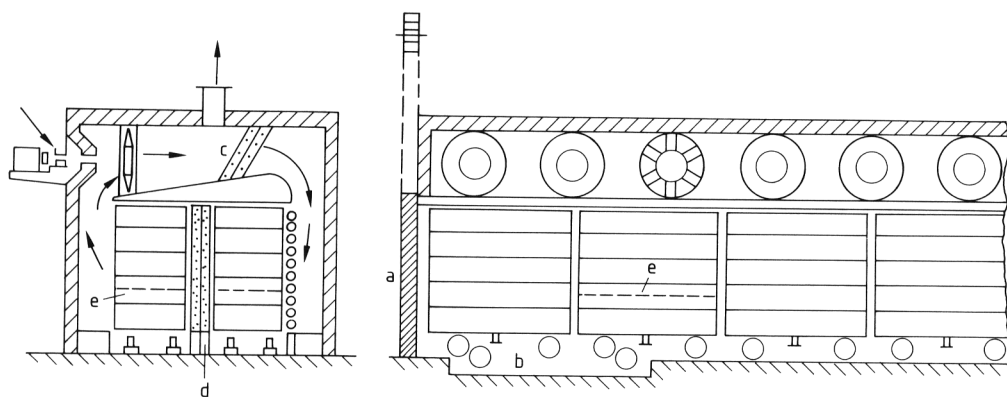


Figure 23. Double-truck dryer for two rows of carts

a) Loading door; b) Cart pool; c) Heater; d) Intermediate heater; e) Racks for loading

The solid is placed upon racks or in trays that are mounted on a cart. A fan circulates warm air through a heater and then through the drying racks or trays. Flow dividers ensure that the air is uniformly distributed. Drying proceeds uniformly and without overdrying portions of the material. The drying process for forced convection dryers is controlled by the amount of exhaust and intake air, as well as its velocity and temperature. Such dryers are employed for processing sensitive materials that require long drying times, i.e., gentle drying. The kilns for some grades of lumber can be 200 m³ or larger. The atmosphere in such chambers can best be regulated by a feedback system with suitable sensors.

Tunnel Dryers. Large quantities of materials are dried in a tunnel in a continuous process. The cart is placed within the tunnel at its entrance and conveyed, usually continuously, but sometimes step by step, along the tunnel to its exit. The moving air can be cocurrent or countercurrent with the direction of the solids.

Sometimes the flow of the drying agent is changed, and it is blown perpendicular to the solid's direction of motion. This can lessen the excessive drying of edges for materials such as plasterboard, and permits different drying conditions in different portions of the tunnel (Fig. 23). Applications of this drying method are freshly lacquered chassis parts and glass plates that have a layer of leather glued to them; they are carried on moving hooks through the drying tunnels. Goods that are in the form of large sheets, such as plasterboard or wood particle board, are moved

by a conveyor system consisting of many parallel rollers that are driven by an interconnecting chain. Many layers of such a roller system can form decks to use the tunnel's space effectively.

Spiral Belt Dryer. A dryer of this type (Fig. 24) is often ideal for materials that require a long, undisturbed drying time. The moist solid is placed upon a circulating belt at a position outside the dryer. The solid remains undisturbed while it dries. The belt enters at the top of the dryer and moves in a spiral fashion toward the bottom. Several blowers rotate about the vertical axis of the dryer and service a particular elevation of it. The air is blown past the solid, onto the heating pipes, and then sucked back across the solid. It is possible to regulate both the temperature and air speed of each vertical drying zone separately.

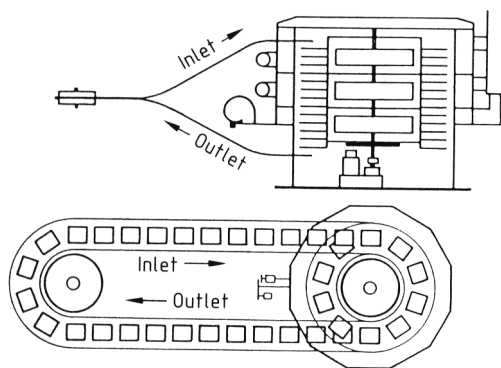


Figure 24. Spiral belt dryer (Courtesy of Babcock BSH)

Segmented Rotating Tray (Wiped-Tray) Dryer. The continuous drying of large quantities of crystalline, granular, or pasty materials that must be dried gently can be effectively done with a segmented rotating tray dryer of the type shown in Figure 25. The solid can have a broad grain-size spectrum. A lazy Susan that slowly rotates around the central axis of the dryer is its main component. Each tray is subdivided into pie-shaped sections by radial slots—60–120 mm wide—through which the material can fall. The moist solid is placed upon the topmost tray in an even layer. A stationary wiping arm comes into contact with the dried surface material and pushes it circumferentially along the disk toward the radial slots. The material that falls through a slot lands upon the disk below, where it initially forms a heap or ball. An arm is used to spread the material into a uniform layer, and the procedure continues until the dried material reaches the bottom of the dryer, where it is removed. Pasty and sticky materials can form clumps in

the early stages of drying. In order to achieve uniform drying, such clumps are subdivided between each disk by an appropriate device.

In the dryer shown in Figure 25, the blowers are centrally located and force the air over the material on one disk and back again over another disk after the air passes through a heating unit. The dryer can have several zones for the circulating air, each having a different temperature. The dimensions for these types of dryers range from 1.2 m in diameter with 8 m² of useful drying surface to 10 m in diameter with 1500 m². The rotational speed of the dryer is specified by the drying time and the number of vertical stages.

Disking Dryers. A circulating disking dryer is advantageous for materials that must be constantly turned over. Like the wiped-tray dryer, it contains a set of vertically stacked, circular trays. In addition, fixed disks of different diameters, in effect, disk-harrow the material on the trays. In this way, the material that is to be dried is both agitated and transported. Attached to the drying chamber is a separate chamber for the fans and heaters to supply and heat the air. An important application of this kind of dryer is for materials moistened by volatile solvents.

Jet Dryers. Dryers of the type shown in Figure 26 blow hot air out of slots or circular holes at a high speed onto the surface of the moist solid. As a consequence of the high air speeds resulting from large rates of circulated air, very large mass-transport coefficients and high drying rates of the liquid near the surface, i.e., the first stage of drying, are achieved. This minimizes the redistribution of the moisture within the solid because of the increased exchange of

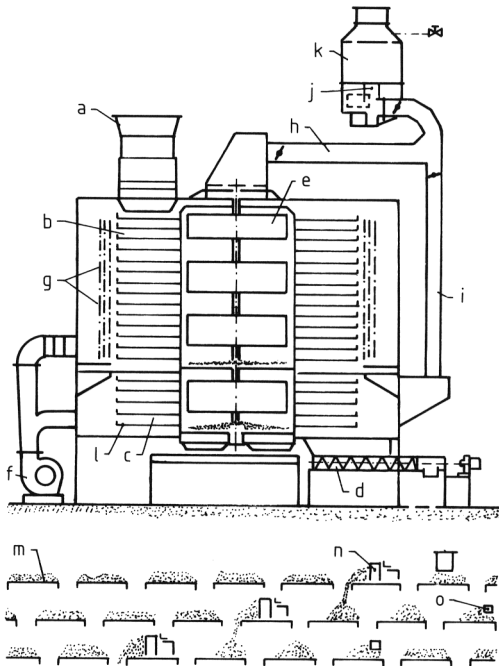


Figure 25. Segmented rotating tray (wiped-tray) dryer
Top: vertical, axial section
Bottom: Detail of the wiping and distributing method
a) Loading device; b) Drying zone; c) Cooling zone; d) Unloading conveyor; e) Turbo fans; f) Fresh air fan; g) Heaters; h) Exhaust duct; i) Cooling air duct; j) Wet washer; k) Demister; l) Segmented tray; m) Segment; n) Wiper; o) Distributor

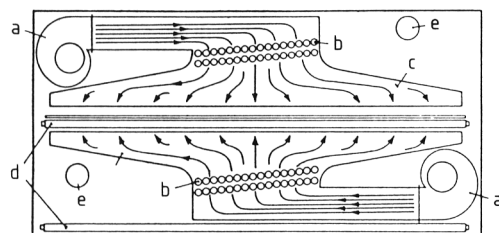


Figure 26. Impinging jet dryer (Courtesy of Deutsche Babcock Anlage)
a) Fresh air fan; b) Heaters; c) Nozzle boxes; d) Roller system loaded with strip material; e) Exhaust

mass. Jet dryers are mostly used to dry flat materials such as wood veneer, cardboard, foils, textiles, or photographic papers.

Continuous sheets of materials, such as coated papers, foils after printing, or photographic film, are transported through the dryer on a cushion of air that can be over 100 m long. Pieces of veneer are placed onto a conveyor belt; extruded pellets, for example, either dry or wet feed, are transported on a continuous stainless steel belt. The speed of the drying air must be adjusted so that the pieces are not blown away. A tentering frame dryer has hooks or clamps for holding the cloth that are attached to a chain that moves through the dryer. The material is laterally constrained in this way, with the result that the fabric undergoes a favorable tensile treatment while drying.

2.1.2. The Solid is Aerated

If air can be blown through a layer of solids, or if the solid can be processed to make this possible,

aeration is the most efficient form of convection drying. Because nearly all of the surface of the moist particles is exposed to the drying agent, maximum heat and mass transfer are achieved for the available conditions. High drying rates are possible even under relatively mild thermal and mechanical conditions.

Through-Circulation Batch Dryer. Agricultural products are often dried by this device. Grain or hay are placed into a container that has a perforated bottom, or onto a rack, and warm air is blown through it. Uniformity of the drying within a pile of cereal can be facilitated with stirring forks that simultaneously transport the material.

More than 100 t/h of grain can be continuously dried in inclined tubular dryers that also aerate the material. There are dryers that resemble silos, and these are filled from the top. The grain slides past roof-like inserts (Fig. 27), as it moves toward the bottom where it is removed from a funnel-shaped collector.

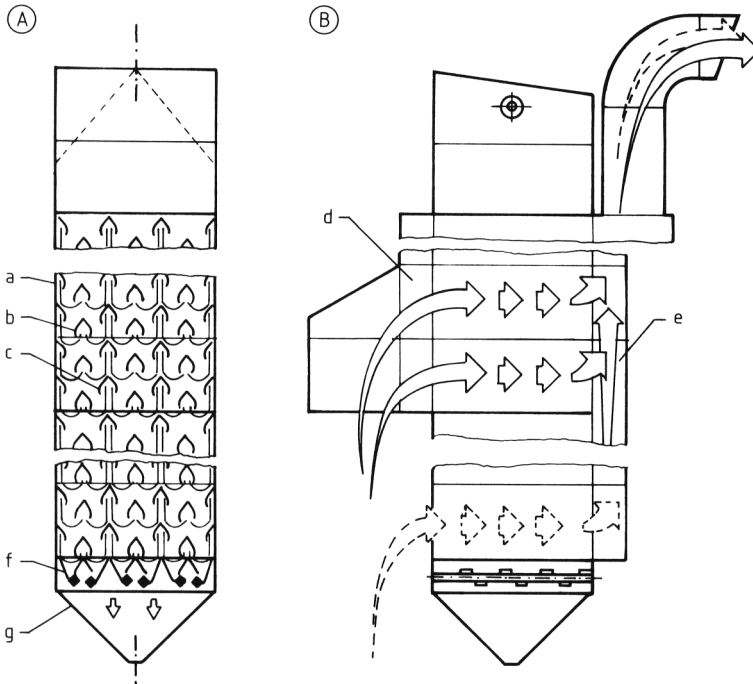


Figure 27. Vertical gravity bed continuous flow dryer

A) Construction of the dryer; B) Air flow (view perpendicular to that in A)

a) Chute; b) Fresh air; c) Exhaust; d) Inlet air duct; e) Exhaust duct; f) Unloading device; g) Funnel

The gas that is used as the drying agent flows through a duct and into the layer of grain via the roof-shaped forms. The gas is subsequently sucked back through similar V-shaped openings that are placed somewhat higher. The uppermost portion of the dryer is not ventilated and is called the sweating zone. Here the material slides past heaters that are usually filled with hot water. The sweating of the grain considerably reduces the necessary drying time. In the lower portion of the duct, a cooling zone is often provided. Fodder is dried with air diluted with (warm) exhaust fumes, but legumes and grains used for food or producing oil are dried with air that is indirectly heated to prevent contamination.

Aerated, Stationary Rack Kiln. Small quantities of fragile materials can be placed on racks that can be put into a kiln. Air is blown through the material. Such ovens are loaded and unloaded by hand.

Aerated, Moving Rack Kiln (Simplizior Dryer). The Simplizior dryer (Fig. 28) is a semi-continuously operating rack dryer that is mainly used by the food industry to treat vegetable products such as parsley, carrots, spinach, mushrooms, as well as spices. Because the moisture content of the drying air increases on its way through the dryer, the racks are moved through the dryer countercurrently to the air. They are loaded with the moist goods and installed in the upper part of the dryer. Then they move toward the bottom, where they are unloaded. The racks are finally loaded with new moist goods, and sent back to the top of the dryer to begin another drying round. The motive power can be supplied by a hand crank in small units, while large installations have power systems that are automatically controlled. In this way the material in all of the racks reaches the same final condition, and the process approaches the efficiency of a fully continuous process.

The dryer that is illustrated in Figure 28 requires removal of the racks above the intermediate heating unit and their reinsertion below it. Intermediate heating of the air is necessary because the air cools after passing through the lower racks, and because very high drying temperatures cannot be used due to the sensitivity of the goods. (The Simplizior dryer is also pro-

duced without an intermediate heater.) Useable surface areas up to 60 m² are common.

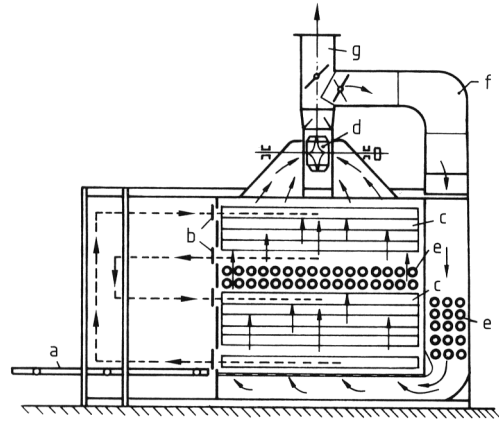


Figure 28. Through-circulation floating rack compartment dryer

Simplizior (Courtesy of Deutsche Babcock Anlage)

a) Elevator; b) Flaps; c) Rack piles; d) Fan; e) Heaters; f) Recirculation duct; g) Exhaust duct

--- Path of solid; — Path of air

Belt Dryers. In belt dryers a loading device that is especially designed for the product is used to place the moist solid on the surface of a belt which passes through a drying chamber that resembles a tunnel. At the end of this chamber the material falls from the belt into a chute for further processing. In some installations the material falls onto another belt that moves in the opposite direction to the first one. Depending upon the characteristics of the material to be dried, multiple passages through the dryer are possible. In this way the material is mixed while drying, and new surfaces are exposed to the drying agent. A shorter, more gentle drying process is the result.

Centrifugal or axial flow blowers are used to aerate the moist materials. The air stream can enter the solid from below or above. The drying agent in belt dryers is commonly supplied laterally so that they are operated as convection dryers with partly recirculating air. The drying agent is heated indirectly with steam or hot water. Fuel oil or natural gas can also be used to indirectly or directly heat the drying agent.

Stepwise heating of the solid is possible with a unidirectional belt dryer, and this allows further control of the drying process. Belt dryers are ideal for friable, molded, granular, or crys-

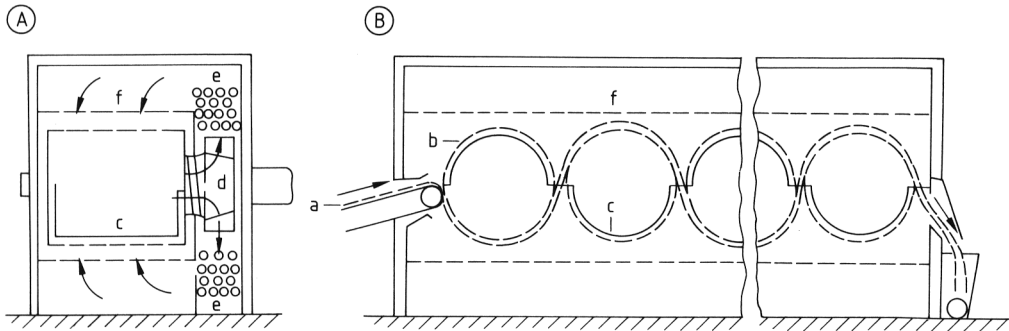


Figure 29. Through-circulation perforated drum dryer for loose, fibrous materials (Courtesy of Fleißner Egelsbach)

A) End view; B) Side view

a) Loading conveyor; b) Perforated drum; c) Cover plates; d) Fan; e) Heaters; f) Air distributor

talline products. They are utilized in all branches of industry.

Aerated Perforated Drum Dryers. This type of machine is employed to dry solids that can form porous layers on curved surfaces. Examples of such materials are cellulose fibers, wool, and cotton. The dryer consists of a series of closely spaced drums with diameters ranging up to 2 m and lengths of 6 m, which turn about a horizontal axis (Fig. 29). The cylindrical surfaces of these drums are made of perforated sheet metal. The material to be dried is transported to the top of one drum and is transferred to the bottom of the next; it moves to the top of the following drum, etc. It is held against the drum by a flow of high velocity air that is sucked into the drums through guides and hemicylindrical baffles at their periphery.

Air-permeable paper is produced on rotating cylinder dryers that consist of only one drum with a surface made of metal screening. The efficacy of these dryers is dependent upon the porosity of the layer of moist solid, the maximum permissible air temperature, and the vacuum that can be achieved within the drum which, in turn, determines the quantity of air that passes through the paper. It takes only seconds to dry the paper in this way.

Rotating Drum Dryers. The drum of a rotating drum dryer (Fig. 30) is longer in relation to its diameter than that of the perforated drum dryers and rotates about a horizontal axis that is slightly inclined. Consequently, the material that is loaded at the upper end slowly wanders toward

the lower end, where it usually falls into a loading hopper. Longitudinal protrusions (flights) inside the kiln distribute the material more or less uniformly over the peripheral surface for drying and promote transport in some instances. These protrusions are often shaped like crosses or quadrants and reduce the drying time in two ways: (1) they constantly stir the solid and (2) intermittently cause it to fall away from the wall as a shower of fine particles through the drying agent, which streams axially along the kiln. Some of these lifting flights do not perform well when the solid is quite dry because they create too much dust, but are very effective for pasty or sludge-like materials. If the drum must be cleaned often, or blockage of the drum can occur, flights that have a relatively simple shape are preferable.

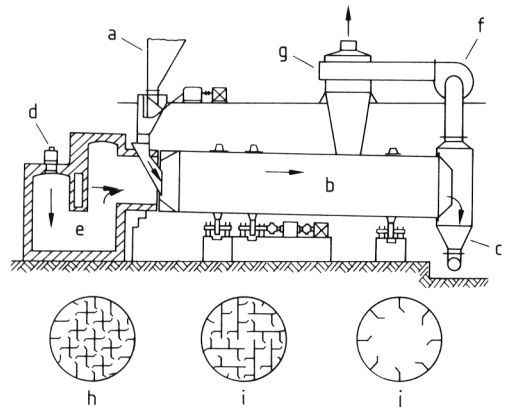


Figure 30. Cocurrent direct-heat rotary dryer and various flight arrangements

a) Feed chute; b) Drum; c) Discharge; d) Burner; e) Combustion chamber; f) Exhaust fan; g) Dust separator; h) Cross-shaped flights; i) Quadrant flights; j) 45° lip flights

The moist material and the drying agent flow either cocurrently or countercurrently. This type of kiln is often direct-fired. They have diameters between 0.3 and 6 m and are used principally for granular and crumbly materials. Pasty substances and slurries are often transformed into crumbs in a short time after they come in contact with the hot drying agent. Some liquid or semi-liquid materials form small clumps when mixed with an already dried portion of the same materials. Then they can be dried with this kind of dryer. To increase the residence time in rotary drum dryers, circumferential baffles are used.

Roto-Louvre Dryer. This particular type of drum dryer has internal guide vanes (Fig. 31) that convey the drying medium in crosscurrent to the moist solid in very close proximity. The solid is simultaneously well stirred. The channels for the drying gas are tapered toward the rear of the dryer to achieve a good flow distribution. This results in a conical dryer, which does not need to be inclined.

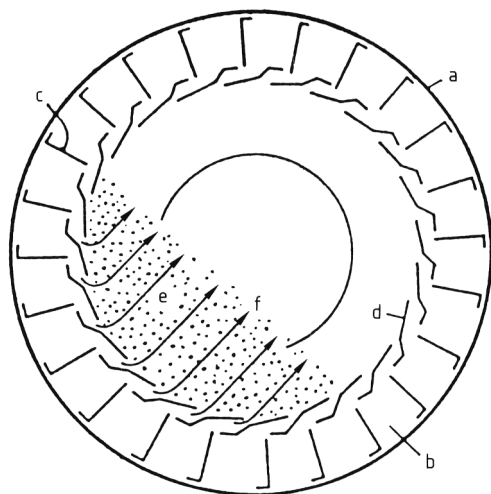


Figure 31. Cross section through a Roto-Louvre dryer (Courtesy of Dunford & Elliott, London)

a) Rotating drum; b) Inlet ducts for hot air; c) Radial guide vanes; d) Tangential guide vanes; e) Moist solid; f) Air flow through the solid

Aerated, Double-Screw Dryer. The moisture in clumps of materials and coarsely fibred or flaky granules can be extracted in an aerated double-screw dryer (Fig. 32). Two parallel screws that rotate closely together convey the

solid over a perforated floor through which the drying agent flows upward. The dryer can be completely sealed so that the drying agent flows in a closed circuit to facilitate the recovery of volatile solvents.

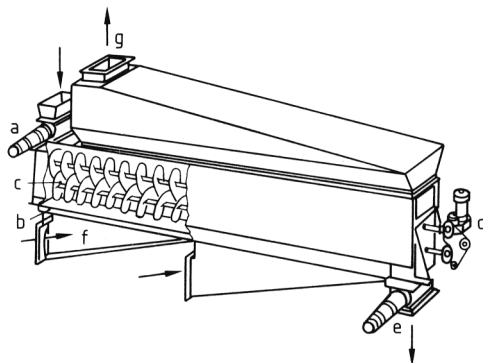


Figure 32. Twin-screw dryer (Courtesy of Werner Pfleiderer Maschinenfabrik, Stuttgart)

a) Product feed valve; b) Fine screen plate; c) Conveyor screws; d) Screw drive; e) Product discharge valve; f) Fresh air distributor duct; g) Exhaust air connector

2.1.3. Large-Scale Agitation of the Solid

Spouting Bed Dryers. These units are noted for their high drying efficiency. One model is illustrated in Figure 33. The solid moves horizontally in a chute and the drying agent flows vertically through a perforated floor to fluidize the solid. These machines can operate continuously, because the solid that enters the dryer via an adjustable opening is transported through it while suspended in the drying agent. The throughput can be increased by belts fitted with scoops to collect and move the material.

To achieve fluidization of the solid with minimum air velocity, vibrating fluidized beds are used. The dryer is mounted on a chute that vibrates under the action of a shaking device. The lengthwise oscillations of the chute serve to transport the material. The residence time of the solid within the dryer can be modified by adjusting the amount of vibration. If the airflow is divided into two sequential streams, the first can be used to dry the solid, while the second can cool it for further processing or packaging. Versions of these kinds of dryers that have a closed circuit for the drying agent can be used to recover solvents.

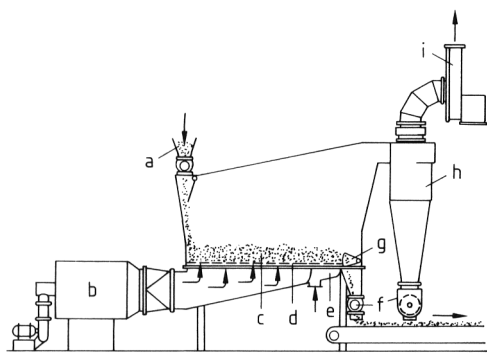


Figure 33. Fluidized bed dryer (Courtesy of Büttner-Schilde-Haas)

a) Fluidized bed; b) Heater; c) Solids feeder; d) Gas distributor; e) Cooling zone; f) Discharge; g) Control baffle; h) Dust separator; i) Fan

Materials that can be suspended in the drying agent are usually powders, crystals, and granular or short-fibered products that remain finely divided or have only a slight tendency to stick or cake. Pastes and slurries are mixed with previously dried material and are then easily fluidized. Solutions and suspensions can be dried by spraying them into the swirling layer with nozzles. The minute solid particles that are present are then covered by a thin film of liquid, which dries quickly, primarily due to the surface evaporation that characterizes the first period of drying. The small particles grow in size by conglomerating with others. Particles are added to the dryer when it is operating continuously to act as seeds. Small dried particles are recirculated; large particles are pulverized, classified, and recirculated. Particles between 0.5 and 5 mm in diameter can be produced from various solutions in this way.

Spin-Flash Dryer. Pastes and high viscosity liquids are often dried best in the type of dryer that is pictured in Figure 34. The dryer is loaded by a screw conveyor or a pump. The material to be dried is first stirred and broken up by a multi-armed paddle that turns at 50–500 rpm. Air is fed in tangentially at the bottom. A kind of fluidized bed is produced in the region of the stirrer. The air flow entrains the smaller, drier particles, and the larger, wetter ones fall back into the stirred region, where they are reduced in size.

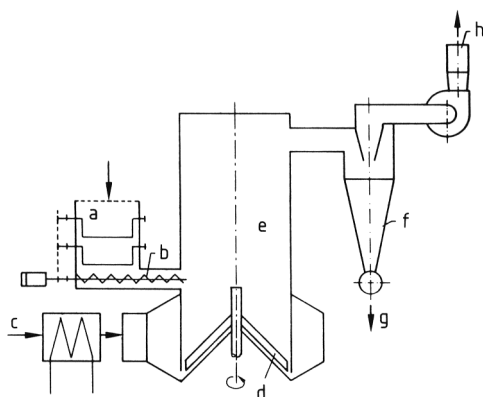


Figure 34. Spin-flash dryer (Courtesy of Anhydro AS, Soborg-Kopenhagen)

a) Moist solid bin; b) Screw feeder; c) Air inlet; d) Stirrer; e) Main drying chamber; f) Material separator; g) Product discharge; h) Exhaust exit

Centrifugal Dryer. Figure 35 shows a centrifugal dryer whose motion serves to subdivide the moist solid and bring it into effective contact with the drying agent. The dryer consists of a stationary closed vessel that has at its base a centrifuge, or possibly two if the unit is large. They whirl the moist solid around in the dryer where the drying agent, usually air mixed with the combustion products of coal, oil, or natural gas, can perform its drying function. The fumes are diluted with enough fresh air to attain the needed inlet temperature and to increase the gas volume sufficiently so that the humidity does not become too high.

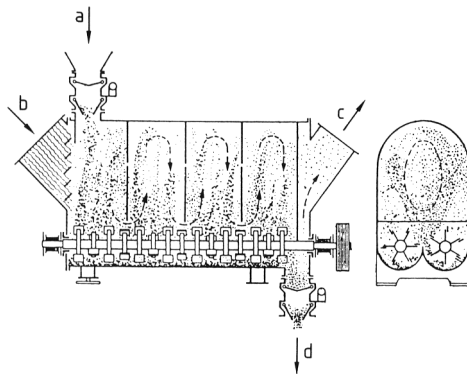


Figure 35. Centrifugal dryer (Courtesy of Hazemag, Münster/Westfalen)

a) Loading zone; b) Hot gas inlet; c) Exhaust outlet; d) Material discharge

There are also dryers that combine the mechanical and aerodynamical methods to entrain the solid in the vortical motion of the drying agent. Machines that swirl the solid are used to dry granules of plastics, salts, coal, and other chemicals.

Centrifugal-Impact Dryer. The unit pictured in Figure 36 functions as a centrifugal dryer and an impact pulverizer. Materials that have an edge length of less than 500 mm and a moisture content of less than 30 % are reduced to a grain size between 0–10 mm and dried in gases that reach 900 °C. Within the dryer a rotating wheel with impact bars catapults the par-

ticles onto hardened plates, which shatter the clumps of moist solid. The pulverized pieces of the moist solid are dried in a stream of hot gases. The smallest particles are entrained in the stream and pass out of the dryer with the drying agent and must be recovered. The coarser particles fall to the bottom of the dryer, where they are removed. Dryers of this type are often used in the sand and gravel industry.

2.1.4. The Solid Moves in the Drying Agent

Pneumatic Conveyor Dryers. Materials that can be pneumatically transported can be dried simultaneously. The simplest form for a dryer encompassing this dual role for the drying agent consists of a vertical tube in which granular or pulverized materials are dried while suspended in a gas or air stream (Fig. 37). The available drying time is only a few seconds: only fine materials, with their high rates of heat and mass transfer, or coarse products, with only surface moisture to be removed, are used in such dryers. Solids that contain internal moisture can only be dried to a limited extent by this method. Sometimes such materials can be dried in a multistaged gas-lift dryer.

The drying agent and the solid move concurrently in air-lift dryers. The moist solid comes into contact with the hottest drying gases when it first enters the dryer. Because the solid is completely submerged in the hot drying gas, the conditions for high heat- and mass-transfer rates are good. The solid has the wet bulb temperature as long as surface evaporation is dominant. Only when this phase of drying is completed does the temperature of the solid begin to rise. This warming process is limited, however, because the drying agent has been cooled by evaporating the moisture. Therefore, sensitive materials can be dried without damage in such dryers, even though the gas inlet temperatures are relatively high. The limited residence time is also a factor. Both organic and inorganic salts that have some moisture after having been centrifuged or filtered can be dried effectively with pneumatic conveyor dryers. Plastic powders, granules, foodstuffs, fodder, wood chips, sand, and quartz can also be dried in this way.

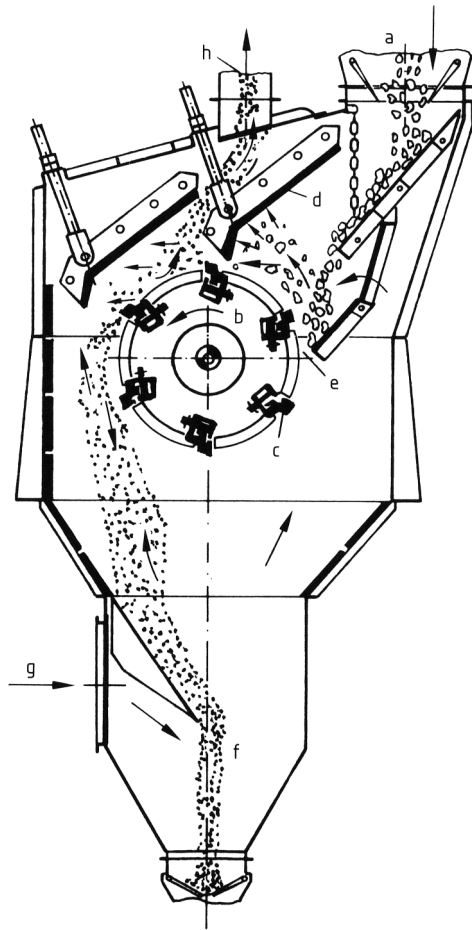


Figure 36. Centrifugal-impact dryer (Courtesy of Hazemag mbH, Münster/Westfalen)

a) Moist solid loading; b) Impact rotor; c) Impact bar; d) Striker plate; e) Adjustable slit; f) Discharge collector; g) Hot-air inlet; h) Exhaust gas exit

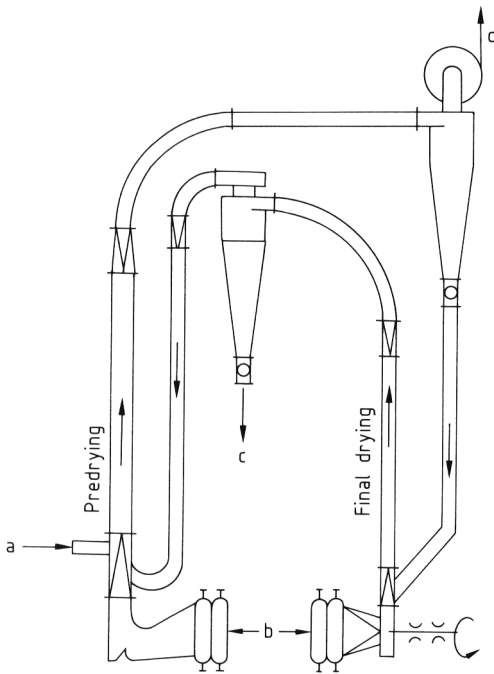


Figure 37. Two-stage pneumatic conveyor dryer (Courtesy of H. Orth, Böhl/Pfalz)
a) Wet feed; b) Fresh air; c) Material discharge; d) Exhaust

Mill Dryers. As the name of the dryer implies, in mill dryers (Fig. 38) the moist solid is simultaneously ground and dried. Although the energy consumption of these devices is relatively large, even that used for grinding the solid ultimately appears in the form of the heat that is necessary for drying. Hot gases also flow through the dryer to achieve the desired drying times. The mill shown in Figure 38 has a loading chute in which the moist material slides to the front surface of a rotating grinding wheel. The particles that this disk produces are carried away by the hot gases into a second grinding chamber of the dryer. Here the solid and entraining gas pass through a series of stationary and rotating pegs that further reduce the particle size. The gases and solids are ultimately forced out of the dryer by the blower.

This kind of dryer can produce powder from granular, caked, or partially liquid materials that can have a moisture content up to 80 % and a representative size of 50 mm. Mill dryers are used to dry and comminute peat clumps at power plants.

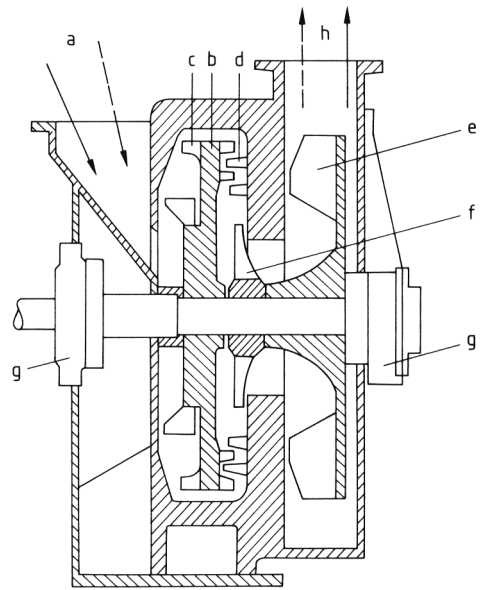


Figure 38. Atritor mill dryer (Courtesy of Alfred Herbert, Coventry, UK)

a) Moist solid and heating gas; b) Rotor; c) Hammer segments; d) Stator; e) Fan; f) Finger separator; g) Bearing; h) To the separator
-- → Heating gas; —→ Moist solid

2.1.5. The Material is Sprayed

Spray drying is used for the drying of pastes, suspensions, or solutions. The moist material is sprayed into the drying agent, and is converted into a powder that is entrained by the gas stream. The volatile liquids vaporize quickly. The gas and the dry powder can be separated at the exit of the dryer.

In this kind of drying process, a uniform fog of moist material should be produced within the dryer. Each type of solid affects the design used to produce a uniform product. The most important types are the disk atomizer (Fig. 39A) and pressure nozzle (Fig. 39B, C). (→ Spraying and Atomizing of Liquids).

Centrifugal disks atomize liquids by extending them into thin sheets, which are discharged at high speeds from the periphery of the rapidly rotating (4000 – 15 000 rpm), specially designed disks (diameter 50 – 350 mm). The speed depends upon the desired size of the particles. This type of atomizer is used for pastes and suspensions because these materials would damage

nozzles by abrasion, or even clog them. Very thick pastes can be treated in disk atomizers but they require a high-pressure pumping system to introduce them into the dryer.

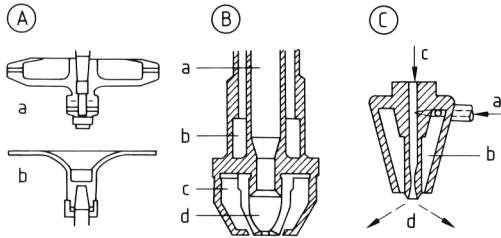


Figure 39. Devices for spraying

- A) Disk atomizer
 a) Suspended installation; b) Standing installation
 B) Pressure nozzle
 a) Fluid delivery; b) Heating or cooling jacket; c) Nozzle support; d) Nozzle orifice
 C) Two-fluid nozzle
 a) Tangential high-pressure air supply; b) Conical expansion and swirl chamber; c) Liquid supply line; d) Spray zone

Powders are produced from a spray nozzle, either a simple nozzle operating under sufficient liquid pressure or a two-fluid nozzle that concurrently sprays streams of liquid and gas – usually air. The resulting mist contains individual particles with diameters between 20 and 300 μm .

Figure 40 shows a two-fluid nozzle that exploits the fact that the speed of sound (critical speed) in a gas–liquid mixture is much smaller than in the gas or liquid phase. The two fluids leave the mixing chamber, which is at a low pressure, and enter an atmosphere where the mixture suddenly expands. The shock wave that occurs at the end of the mixing chamber causes the liquid – with suspended solids in some cases – to be distributed into a fine mist with a narrow size spectrum.

Because the liquid is transformed into minute drops, a very large surface area is placed in contact with the drying agent. Very short drying times – from fractions of a second to a maximum of a few seconds – are the result.

One or more powderizing systems can be installed at the top of a cylindrical structure, which is often as high as 20 m and several meters in diameter. Hot gases are introduced into the drying tower at the bottom or the top. The final product falls into a conical hopper at the bottom of the dryer, where it is unloaded.

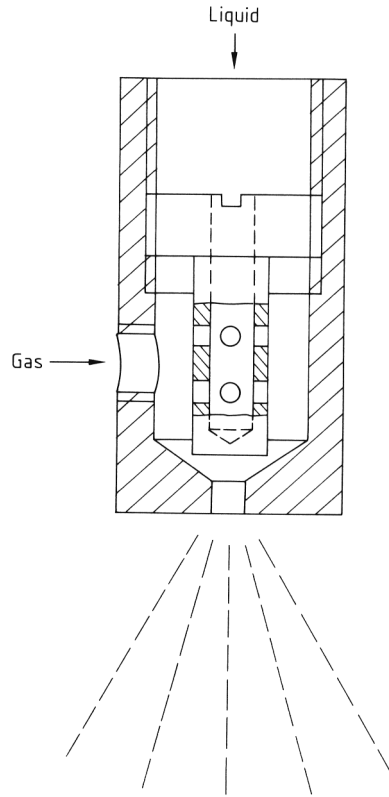


Figure 40. Two-fluid sonic nozzle
 (Courtesy of Caldyn, Ettingen, FRG)

Spray dryers are particularly suitable for drying solids that are temperature sensitive. Examples are milk products, baby foods, eggs, blood and blood plasma, pharmaceutical products, chemicals, dyes, plastics, glues, tannin, and soaps. An advantage of these dryers is the high solubility of the powders that are produced.

2.2. Contact Drying

In contact drying, the heat is directly transferred to the solid from a heated surface upon which it rests. The solid may be either stationary or be continually transferred from one hot surface to another.

2.2.1. Flat and Strip Materials

Materials that are flat or in strips, such as textiles, paper, or cardboard, are dried with a drum dryer. The moist material is wrapped around a

series of rotating, horizontal cylinders that are usually heated internally with steam. The steam and its condensate enter and leave the cylinder through hollow-journals, often the same journal. Materials that have a low strength when moist, e.g., felt and cotton, move between the drums on endless belts. The belts press the solid against the drying drums and simultaneously absorb some of the moisture. This moisture must be subsequently removed from the belts (Fig. 41). The possibility of introducing air between the drums and the moist material in rapidly rotating drum dryers is reduced by the pressure that the belts exert against the material. Consequently, the contact resistance to heating is reduced, and the heat transfer between the drum and product is improved.

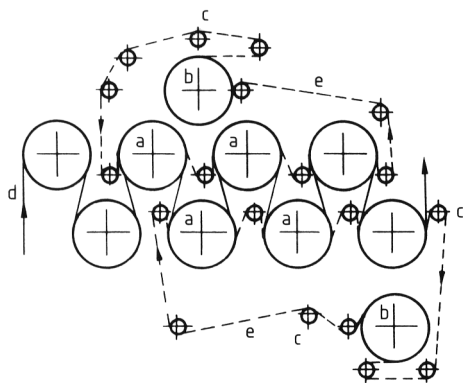


Figure 41. Schematic of a multicylinder dryer with guiding belt

a) Drying cylinders for the moist solid; b) Drying cylinders for the guiding belt; c) Guide rollers; d) Moist material; e) Guide belt

2.2.2. Low-Viscosity Materials

Roller Dryers. In order to contact dry solutions of organic or inorganic material, a continuously operating roller dryer is almost always used (Fig. 42). They are usually selected because of their effective utilization of heat.

The material flows onto the drying roll as a thin layer. The liquid is vaporized by the heat coming from the heated rollers. Shortly before the dried solid reaches the end of the dryer, it is peeled away from the hot surface by a scraper to produce a film, coarse or fine flakes, or a powder.

Some of the methods of applying the moist material to the rollers are shown in Figure 43. Each one has its particular uses, depending upon the adhesion and consistency of the moist solid.

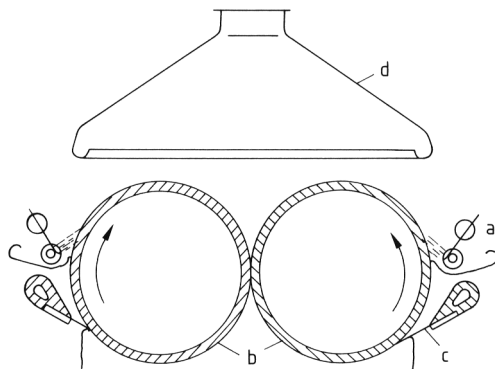


Figure 42. Double-roller spray dryer (Courtesy of Escher Wyss)

a) Spraying apparatus; b) Drying rollers; c) Scraping knife; d) Moisture exhaust

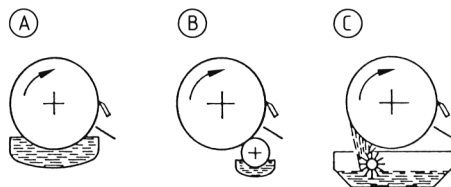


Figure 43. Methods for feeding the moist solid for a roller dryer

A) Submerged roller; B) Distributing roller; C) Barbed roller

The rollers are usually heated internally with steam, although hot water or heat carrier oils are sometimes used. Induction-heated drying cylinders are also available; they can produce controllable surface temperatures between 40 and 400 °C.

Hoods can be placed over the dryer to reduce the ambient pressure and facilitate drying. The dryer can also be completely encased to make it airtight and dustproof. In some applications where increased drying efficiency is needed, the roller is additionally heated with a stream of hot air or exposed to a radiant heater (Fig. 44).

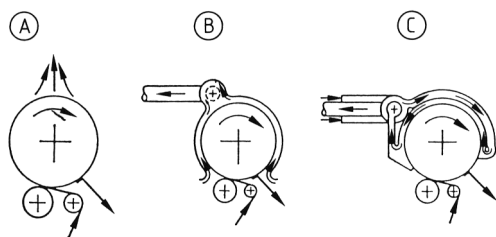


Figure 44. Aerating a single-roller dryer

A) Dryer without a hood; B) Dryer with hood and exhaust;
C) Dryer with hood, warm air supply, and exhaust

2.2.3. Pasty Materials

Roller dryers are also effective for drying pasty or creamy materials if they can be satisfactorily applied to the rollers. A proven single-roller device is shown in Figure 45.

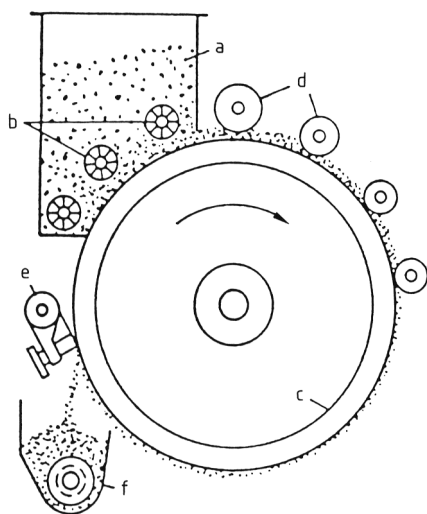


Figure 45. Single-roller dryer for mealy materials

a) Feed container; b) Stirrers; c) Drying roller; d) Pressurizing rollers; e) Scraping knife; f) Discharge

Grooved Roller Dryer. A special type of roller dryer reduces the moisture of pastes by 8–10 % and produces short segments for further drying steps. The paste is not rolled out into a thin layer, instead it is forced by a special roller into the grooves of the drying roller. As the roller turns, the material is pressed and thickened. Finally, a serrated scraper removes the dried material. To dry the solid completely

a belt dryer is added. The drying of materials such as stearates, carbonates, clay, kaolin, white lead, or titanium dioxide are some special applications of this kind of dryer.

Hollow-Screw Heat Exchanger. Hollow-screw heat exchangers (Fig. 46) have proved useful for the continuous drying of paste. This dryer consists of a trough that contains one or two hollow screws. The screws turn in the same or the opposite directions, and partially overlap. Screws turning in the same direction are preferred for pastes because of the greater overlap and the self-cleaning action. Hot water, saturated steam, or hot organic liquids serve to provide the heat.

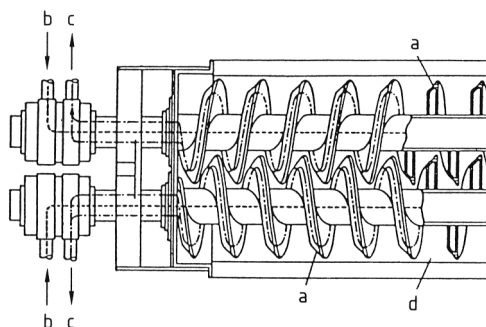


Figure 46. Hollow-screw heat exchanger (Courtesy of Lurgi)

a) Hollow-screw conveyors; b) Inlets for the heating agent;
c) Outlets for the heating agent; d) Trough

List AP Dryer (All Phase Dryer). The dryer shown in Figure 47 can be used for materials that can range from fluid or pasty to putty-like or granular during the drying process. It is also suitable for substances that are sticky or form crusts. A suitably designed horizontal housing surrounds the main roller, which has disks attached to it. This roller rotates in the opposite direction to a cleaner roller that has rectangular hoops that stir the material. The cleaner roller's speed is four times that of the main roller, whose surface is cleaned by it. Kneadable solids adhere to the disk protrusions on the main roller and scrape against the housing to scour and clean it. The throughput of the device can be controlled by the orientation of the rollers. The housing, its lid, the hollow main roller, and the disk elements are heated with steam, hot water, or hot oil.

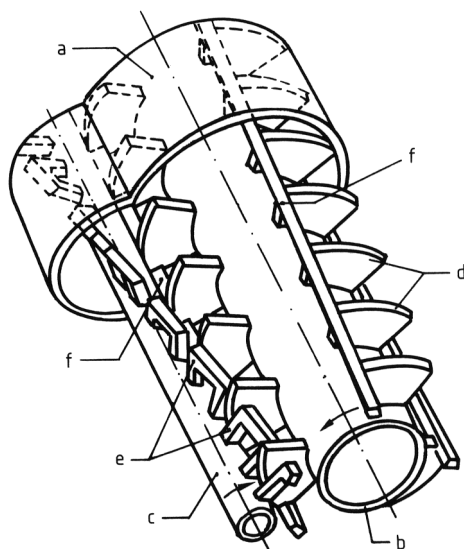


Figure 47. Contact dryer with stirrer and kneader (Courtesy of List, Prattein)
a) Double-walled container; b) Main shaft; c) Cleaning shaft; d) Cleaning disk; e) Square-hoop stirrer; f) Kneading bars

2.2.4. Granular Materials

Rotary Dryer. The heat necessary for drying is transferred through the peripheral walls of a rotary dryer in contact drying. Only a small amount of air is necessary to carry off the moisture that is taken from the solid. Accordingly, the air velocity in these units is quite low. This is advantageous when drying materials that dust easily or form dust during drying. If necessary, ducting can be installed to introduce gases into the drum where the solid is drying.

Rotary dryers are preferred for drying washed ores, coal, and cement. Such materials are constantly turned over and mixed by lifting flights attached inside the drum.

Rotary contact dryers are produced in two main types. The first is constructed with integral heating pipes within the drum. The solid falls in a shower past these hot pipes once during each revolution of the drum. In the second type, the moist solid is in tubes that are attached to the walls of a drum into which steam is fed. The steam condenses on the surface of the tubes, heating the moist solid within. The drum is inclined to the horizontal so that gravity transports the material down the tubes, but some assistance

is provided by the flow of vapor that ensues in the tubes.

Screw Conveyor Dryers. Inside the drum, screw conveyor dryers (Fig. 48) have a rotor that is fitted with many small paddles that constantly force the moist solid into contact with the hot wall, as well as move it along the axis. The residence time of the solid in the dryer is regulated by changing the angle of the paddles.

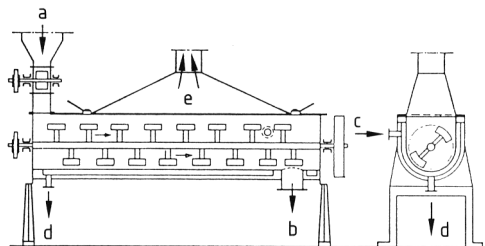


Figure 48. Screw conveyor dryer (Courtesy of Büttner-Schilde-Haas)

a) Moist solid loading; b) Dried solid discharge; c) Inlet for heating agent; d) Outlet for heating agent; e) Solvent vapors

Cone-Worm Dryer. A cone-worm dryer operates along the inclined wall of a vertical funnel-shaped container. The chamber is sealed and equipped with a heating jacket. The screw serves to transport the material to the top and to produce a gentle stirring of the moist solid.

Tray Dryers. When contact drying is employed, the trays (Fig. 49) are heated. Different heating intensities on the different trays provide the optimum conditions for drying. In this way, for example, the material can be cooled in the lowest levels of such dryers. The vapor is removed by warm air flowing countercurrently.

Spiral Tube Dryers. The drying of solids that range from granular to powdery is facilitated by spiral tube dryers (Fig. 50). The material is only momentarily in contact with the heated surface of the tube and is transported pneumatically. Residence time in the dryer is but a few seconds. These dryers require only a small amount of gas. Therefore, the drying of solids wetted by solvents can be done very economically with inert gases flowing in a complete circuit that includes a solvent recovery system.

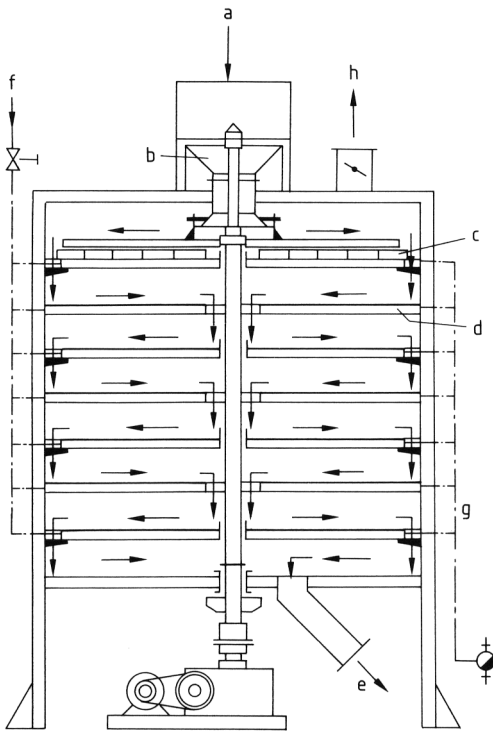


Figure 49. Tray dryer (Courtesy of Büttner-Schilde-Haas)
a) Moist solid loading; b) Rotating tray feeder; c) Rakes (only drawn for topmost level); d) Heated tray; e) Product discharge; f) Steam; g) Condensate; h) Exhaust

Spiral tube dryers find application in processing plastic granules, starches, bread crumbs, and copper powder.

2.3. Radiant Heat or Infrared Drying

Very short drying times are possible with infrared radiation sources that transmit large amounts of energy per unit of surface area to the solid in the form of heat. This method of drying is costly because of the electrical energy. It is only economical for drying long runs of similar materials that have a sufficiently thin surface film.

The intensity and emission spectrum of the radiation must be optimized with respect to the moist solid to keep the energy costs low and to prevent excessive heating of the solid. Ovens with conveyor systems are often divided into zones to achieve this optimization; the individual

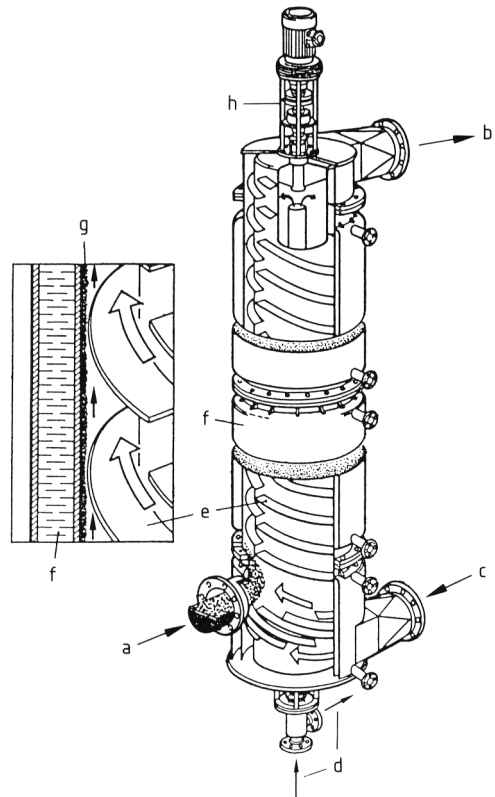


Figure 50. Spiral tube dryer (Ruhchemie system, greatly shortened) (Courtesy of Werner & Pfleiderer)
a) Moist solid; b) Dry solid; c) Transporting air; d) Heating liquid; e) Air baffles; f) Heating jacket; g) Product path; h) Compactor drive

radiation sources can be adjusted to match the conditions of the solid (\rightarrow Radiation Heating).

The main use of this method is the drying of painted surfaces because warming occurs rapidly, forcing the solvents within the paint to move to the surface, which inhibits the formation of an undesirable surface skin. This method of drying is also important for drying thin-walled ceramic products, which can be dried quickly but without cracks by this method.

A combination of radiant and contact drying is effective if the drying time or the size of the dryer must be reduced. An example of such a combination dryer is shown in Figure 51. The dryer is provided with a means for jet drying a woven belt and a radiant heater to predry the material. The rapid drying of the fabric surface

hinders the undesirable migration of dyes and other chemicals to the surface.

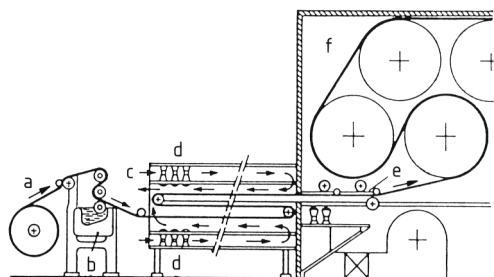


Figure 51. Predryer for textiles (Courtesy of Philips)
a) Fabric; b) Impregnating trough; c) Air inlet; d) Infrared radiators; e) Sheet-metal reflector; f) Main dryer

2.4. Dielectric Heating

Drying with high-frequency heating has an advantage over other methods of drying: the temperature within the moist solid rapidly rises. The internal temperature can be maintained at a prescribed value regardless of the surface temperature. When wood is dried by this means, the moisture distribution can be adjusted so that the surface is always more moist than the interior. As a result, compressive stresses are induced in the surface fibers, strengthening the product, whereas the other means of drying tend to weaken the material and produce cracks. Only a few hours are needed to dry wood and ceramic goods with high frequency (\rightarrow Electrically Generated Heat).

Relatively high energy and installation costs are associated with this method of drying so that it is only cost effective to dry particularly valuable materials such as special hardwoods, large ceramic pieces, or temperature-sensitive foodstuffs and gourmet items.

2.5. Vacuum and Freeze Drying

Almost all dryers that operate at atmospheric pressure and supply the necessary heat by conduction or radiation can be converted to a vacuum dryer. The principal difference in the vacuum dryers are their seals and the means to produce the vacuum. Continuously operating

vacuum dryers require, in addition, special devices for loading and unloading. Drying under reduced pressure is advantageous for materials that are temperature sensitive or easily decomposed because the vaporization temperature is reduced. Also, drying times in vacuum dryers at the maximum temperature are shorter. When drying materials containing organic solvents in vacuum dryers, the solvents are recovered more economically than with convection dryers because the humid drying agent need only be cooled to the condensation temperature of the solvent at the reduced pressure. Vacuum dryers are most often used to dry pharmaceutical products and foodstuffs. If the substance to be dried is poisonous or potentially explosive, vacuum drying lessens the emission of poisonous gas or vapor into the environment.

The simplest form of a vacuum dryer for batch drying is the vacuum shelf dryer. The moist solid lies on a heated plate. Improved heat transfer with higher efficiency is obtained in the vacuum tumble dryer (Fig. 52), in which the moist solid is constantly agitated and mixed. An example of a continuously operating vacuum dryer is a roller dryer with one or two rollers. Air-lift dryers that operate at reduced pressures are effective when large amounts of materials must be dried at low temperature and only a relatively small amount of moisture must be removed.

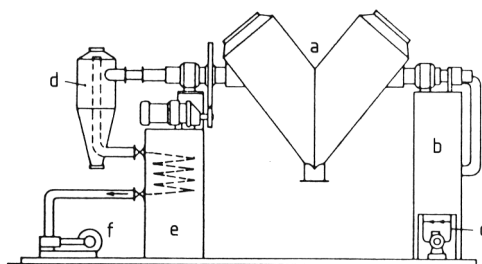


Figure 52. Vacuum tumble dryer (Courtesy of Patterson-Kelley)
a) Rotating container; b) Heating boiler; c) Pump; d) Dust separator; e) Condensor; f) Vacuum pump

Freeze Drying. Freeze drying is characterized by the removal of water (sublimation of ice) from the solid at temperatures below 0°C and reduced pressure. Freezing halts nearly all the chemical and biological processes in the

material so that it is biochemical, physiological, and therapeutic characteristics remain essentially unchanged. Accordingly, this method of drying is used to process high-value foods, fruit juices, spices, tea, coffee, pharmaceuticals, virus and bacteria cultures, vaccines, and preparations containing protein.

A schematic diagram of a freeze dryer is shown in Figure 53. Usually the freezer is a separate first stage and then the solid is vacuum-dried, but in some systems one apparatus performs both functions. Shallow pans that contain the solid are heated by conduction in the dryer. The vapors condense as ice upon reaching the cooling surfaces. These surfaces must be thawed at the end of the process when the condenser is isolated from the drying chamber by closing a valve. The dryer is then evacuated with the aid of a diffusion pump.

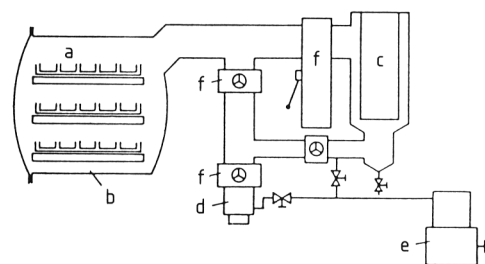


Figure 53. Oven vacuum drying (Courtesy of E. Leybolds)
a) Heated trays with moist solid; b) Drying oven; c) Condenser; d) Diffusion pump; e) Booster pump; f) Shut-off valves

The continuous operation of a freeze dryer that processes foodstuffs is accomplished with a vacuum disk dryer. Such a unit is characterized by considerably shorter drying times than a vacuum chamber dryer (→ Refrigeration Technology).

3. Selecting, Sizing, and Energy Requirements of Dryers

3.1. Choosing the Type of Dryer

The choice of a particular dryer type is mainly determined by the characteristics and production rate of the material that requires drying. Often several types would be suitable so that operat-

ing and economic aspects become the decisive criteria.

3.1.1. The Role of the Material Properties of the Solid

The mechanical properties of the moist solid when it arrives at the dryer determine the ways the material can be loaded into and transported through the dryer. Lumpy, granular, and crumbly materials can remain stationary (as in simple drying chambers, Simplizior, tunnel, or screw dryers), or they may be moving in respect to their supporting elements (as in fully-automated rack dryers, belt dryers, air-lift dryers, drum dryers, cyclones, and spiral tube dryers). Liquefied and pasty materials can be converted into fine drops (spray dryer), or thin layers (roller dryer), or they can be transformed into a crumbly material by partial drying (grooved roller dryer).

The thermal sensitivity of the material determines the temperature at which the heat can be transferred safely and the residence time in the dryer. If low temperatures are necessary, moisture removal can be achieved with a vacuum dryer. Small residence times are possible in forced convection dryers, spiral tube dryers, and spray dryers.

Materials that are chemically insensitive can be dried in direct contact with the hot drying agent, either air or combustion products. If the moist material is chemically sensitive, an inert gas must be used as the drying agent or some other heating method must be applied.

In the event that an organic solvent is present, it may be economical to recover it. In some cases the solid or the moistening liquid may be flammable or toxic. In such cases, completely enclosed dryers, such as vacuum dryers or special contact dryers, are to be recommended.

3.1.2. Production Rate

The throughput of the solid determines whether the dryer is to be operated in a continuous or batch mode. Batch operation requires a high energy consumption and worker effort per unit mass of dry product, but installation costs are relatively low. Nevertheless, this method of drying (a simple drying oven or chamber) is often

economically viable for products with a small throughput or often changing properties.

When it is necessary to dry a well-specified product at a high production rate, a continuous dryer is advantageous. Even though the initial costs of such installations are high, the standardized physical and geometric characteristics of the product permit optimization of the energy requirements for this mode of operation. Moreover, the manpower necessary to operate the system is quite small. Most of the common dryer types are able to operate in the continuous mode. The efficiency of a dryer is largely determined by the amount of moisture that can be removed per unit area or volume of the dryer, and the amount of heat that is necessary to vaporize the liquid on a unit mass basis. Table 2 gives information about these parameters.

Table 2. Vaporizing effectiveness and heat consumption of dryers

Dryer	Vaporizing effectiveness, kg H ₂ O m ⁻² h ⁻¹ *	Heat consumption, kJ/m ³ h vaporized H ₂ O
Air-lift dryer (d = particle diameter)	d = 0.5 mm: 100 kg m ³ h ⁻¹ d = 1 mm: 20 kg m ³ h ⁻¹ d = 5 mm: 4 kg m ³ h ⁻¹	3700–8800
Belt dryer		4000–5000
Centrifugal dryer	90 kg m ³ h ⁻¹	3300–3500
Compartment dryer	0.1–12 (ventilated) 0.1–15 (flown over)	5600–13 000
Cylinder dryer	7–25	2900–5700
Drum dryer	25–50 kg m ³ h ⁻¹	4000–8000
Kiln	20	5000–5800
Roller dryer	5–60	2900–5700
Rotating steam tube contact dryer		3800–6300
Roto-Louvre dryer	35–75	3500–10 000
Screw conveyor dryer	5–15 (high humidity) 0.5–2.5 (low humidity)	3400–5600
Spiral tube dryer	500 kg H ₂ O m ³ h ⁻¹	3400
Spray dryer	1.5–48 kg m ³ h ⁻¹	4600–11 000
Tray dryer	4–8	
Vacuum chamber dryer	0.15–1	2900–4600
Vacuum paddle dryer	10–15	2900–4200
	0.4–0.6 **	10 000
Wiped tray dryer	3.5–4	3500–9200

* If not noted otherwise.

** With intensive terminal drying.

3.1.3. Dryer Ventilation

The ventilation of a dryer is important, and the various possibilities are given according to a scheme by GÖRLING in Figure 54.

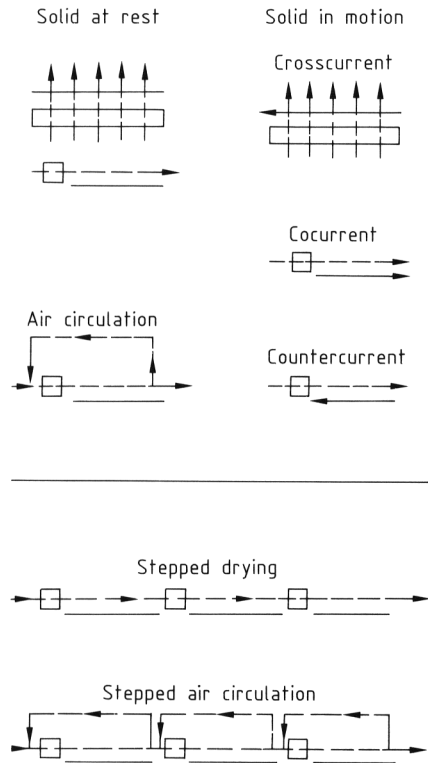


Figure 54. Various arrangements between solid, heaters, and drying agent
-- , → Solid; -- → Drying agent; □ Heaters

Stationary Solids. Solids that remain stationary in a convection dryer usually encounter a flow that is parallel to the surface on which they rest. However, it is possible to blow the air through a layer of granular material. This requires more energy to realize a given amount of air flow, but shorter drying times are possible so that the total energy consumption can remain satisfactory.

The usual manner of using air as a drying agent is to constantly circulate it past the moist solid while adding only a fraction of fresh air to the system. This is economical and minimizes the possibility of uneven drying or overheating the solid, which otherwise usually occurs near the air inlet duct. Through such a circulating system, the drying process can be satisfactorily matched to the characteristics of the solid by adjusting the temperature and speed of the air. Moreover, the influence of the daily atmospheric conditions are easy to compensate with this system.

Moving Solids. If the solid is moving in the dryer, the stream of air can be flowing in the same, opposite, or perpendicular direction to produce cocurrent, countercurrent, or cross-current drying, respectively.

In *cocurrent drying* the hot, dry air encounters the solid in its most moist condition at the dryer's entrance. As a consequence of the large temperature and humidity differences between the solid and the air at the beginning of the drying process, the drying rate is high. However, as a result of increasing humidity and decreasing temperature of the air along its path, the drying rate decreases continuously and becomes quite small near the end of the dryer. Thus with cocurrent drying, a small residual moisture content in the solid is not realizable with economical amounts of drying agent. Cocurrent drying is economically attractive if the dry solid is sensitive to high temperatures, the moisture removal does not have to include an extensive part of the hyroscopic moisture, and the initial high temperature in the dryer is not deleterious to the properties of the solid.

In *countercurrent dryers* the hot, fresh air comes in contact with the solid when it is at the end of its drying process; the cooled, moist air flows past the fresh, moist solid at the beginning. At first the solid is dried slowly, which is beneficial for products such as clay, but at the end of the drying process the solid is exposed to very high temperatures. Countercurrent dryers are not suitable for temperature-sensitive products.

A matching of the drying air temperature with the requirements of the material to be dried is not possible in one-stage *crosscurrent dryers*. For this reason the solid must not be sensitive to high temperatures. The advantage of the method is that short drying times can be achieved. Using crosscurrent dryers which are subdivided in zones with different air temperatures, the conditions in cocurrent as well as in countercurrent dryers can be approximated.

As with stationary solids, moving solids can be dried more economically and uniformly when a circulating system for the drying agent is used. A further refinement consists of heating the air at several places along its path through the dryer. In this manner, the dryer is subdivided into several zones, and the temperature of the solid in each zone can be easily regulated. However, the

change of humidity and the velocity of the drying agent are prescribed. In order to freely adjust the air velocity as well, the zone construction can be combined with the circulation of the drying agent. In each zone of this type of dryer, the air is circulated in large amounts and can be kept at the desired temperature by individual heaters. The humidity is adjusted by adding small amounts of air from the next zone, which is then mixed with the primary air. This method can be used for stationary or moving solid.

3.2. Sizing the Dryer

After the type of dryer that is needed has been determined, then its size (major dimensions) must be specified, which cannot always be done theoretically. The engineer often needs to turn to values obtained from existing units or experimental tests.

3.2.1. Batch Dryers

Drying with Constant Air Properties. The conditions of the air are practically constant during the entire drying process when large amounts of air are used or a large surplus of fresh air is circulated. If the normalized drying rate curve $\dot{\nu}(\xi)$ is known, then the drying time t can be calculated:

$$\frac{A\dot{m}_1}{M_s(X_{\text{crit}} - X_{\text{eq}})} t = \int_0^{\xi_i} \frac{d\xi}{\dot{\nu}(\xi)} \quad (30)$$

A is the surface area and M_s is the mass of the dry solid. The drying rate in the first period of drying is \dot{m}_1 and is determined from Equation (15):

$$\dot{m}_1 = \rho_g \beta_g^0 [Y^*(T_1) - Y]$$

Drying with Variable Air Properties. If the fresh air surplus is small or the amount of circulating air is limited, the conditions of the drying agent change considerably as it flows in the dryer. The normalized moisture content of the solid ξ is not only a function of time but also depends upon the path length of the drying agent z . In the analysis of the drying process, it is useful to introduce the dimensionless drying time τ

$$\tau = \frac{\rho_g \beta_g^0 A [Y^*(T_1) - Y(z=0)]}{M_s (X_{\text{crit}} - X_{\text{eq}})} \quad (31a)$$

and the dimensionless path length ζ

$$\zeta = \frac{\rho_g \beta_g^0 A}{\dot{M}_g} \cdot \frac{z}{L} \quad (31b)$$

in which \dot{M}_g is the mass flow rate of the drying agent and L is the length of the dryer. The fundamental equation for the temporal and spatial distribution of the solid's moisture $\xi(\zeta, \tau)$ is

$$\frac{\partial^2 \xi}{\partial \tau \partial \zeta} + \dot{\nu}(\xi) \frac{\partial \xi}{\partial \tau} - \frac{1}{\dot{\nu}(\xi)} \cdot \frac{d\dot{\nu}}{d\xi} \cdot \frac{\partial \xi}{\partial \zeta} \cdot \frac{\partial \xi}{\partial \tau} = 0 \quad (32)$$

This equation assumes that the partial pressure of the vapor is small with respect to the total pressure, and that the normalized drying rate curve $\dot{\nu}(\xi)$ is independent of the condition of the drying agent. In addition, the critical moisture content X_{crit} must be independent of the drying rate. Solutions to this equation are given in the literature [9]. A qualitative picture of the temporal and spatial moisture distribution in the solid is given in Figure 55. The initial moisture content is ξ_i , and $\xi = 1$ corresponds to the critical moisture content. At $\tau = \tau_{\text{crit}}$, the solid's critical moisture content is achieved at the entrance of the dryer, $\zeta = 0$. Subsequently, the location of the critical moisture content of the solid $\zeta_{\text{crit}}(\tau)$ is shifted through the dryer. Whenever $\zeta_{\text{crit}} > \zeta_L$, the entire solid would be in the second or possibly third stage of drying.

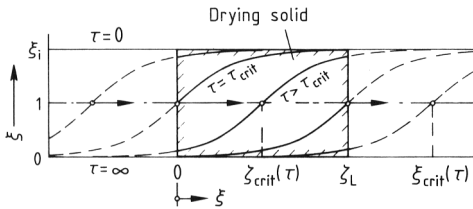


Figure 55. Moisture distribution in a solid as a function of dimensionless time τ

In order to estimate the extent of drying, it is often sufficient to approximate the normalized drying rate curve $\dot{\nu}(\xi)$ with the linear approximation

$$\begin{aligned} \dot{\nu} &= \xi \text{ for } 0 \leq \xi \leq 1 \\ \dot{\nu} &= 1 \text{ for } 1 \leq \xi \leq \xi_i \end{aligned}$$

In this case Equation 32 has an analytical solution. For

$$\tau_{\text{crit}} = \xi_i - 1 \quad (33)$$

in the region $\zeta \geq \zeta_{\text{crit}}$ and $0 \leq \tau/\tau_{\text{crit}} < \infty$

$$\xi(\zeta, \tau) = \xi_i - (\xi_i - 1) \exp[-(\zeta - \zeta_{\text{crit}})] \quad (34)$$

is obtained. In the region $\zeta \leq \zeta_{\text{crit}}$ and $0 \leq \tau/\tau_{\text{crit}} < \infty$ the result is

$$\xi(\zeta, \tau) = \frac{\xi_i}{1 + (\xi_i - 1) \exp[-\xi_i(\zeta - \zeta_{\text{crit}})]} \quad (35)$$

The dimensionless location of the critical moisture content ζ_{crit} can be calculated by

$$\zeta_{\text{crit}} = \ln(\tau/\tau_{\text{crit}}) \quad (36)$$

for $\tau/\tau_{\text{crit}} < 1$, and by

$$\zeta_{\text{crit}} = \frac{1}{\xi_i} \ln \frac{\xi_i \exp[(\xi_i - 1)(\tau/\tau_{\text{crit}} - 1)] - 1}{\xi_i - 1} \quad (37)$$

for $\tau/\tau_{\text{crit}} \geq 1$. Even though Equations (36) and (37) encompass all values of ζ_{crit} between $\pm \infty$, only the values between 0 and ζ_L have a physical meaning.

3.2.2. Continuous Dryers

Useful suggestions and short-cut methods for the sizing of drum, convection, and spray dryers can be found in [10]. The following theoretical analysis utilizes the same simplifying assumptions that were used in the analysis of batch drying (see Section 3.2.1).

Drying with Constant Air Properties. The drying time t is determined by Equation (30). This corresponds to the residence time of the solid in the dryer. If u is the speed of the conveyor, then the necessary dryer length is $ut = L$.

Drying with Variable Air Properties. In contrast to batch drying, the location of the solid's critical moisture content within the dryer is independent of time. The basic equation for the spatial variation of the moisture in a cocurrent dryer is

$$\frac{d\xi}{d\zeta} + (\xi + C) \dot{\nu}(\xi) = 0 \quad (38)$$

In Equation (38) C is the so-called *excess air factor*, which is defined as

$$C = \frac{[Y^*(T_1) - Y(\zeta=0)] \dot{M}_g - (X_i - X_{eq}) \dot{M}_s}{(X_{crit} - X_{eq}) \dot{M}_s} \quad (39)$$

If $C = 0$, the air exactly reaches saturation when the solid has reached its equilibrium moisture content. In practice, $C > 0$ is used. To obtain an order of magnitude, Equation (38) can be integrated with a simple function for the normalized drying rate curve. For this purpose the linear approximation $\dot{\nu}(\xi) = 1$ for $\xi \geq 1$ and $\dot{\nu}(\xi) = \xi$ for $\xi \leq 1$ is used. For the region $\xi \geq 1, \zeta \leq \zeta_{crit}$ the result is

$$\xi = (1+C) \exp[-(\zeta - \zeta_{crit})] - C \quad (40)$$

For the region $\xi \leq 1, \zeta \geq \zeta_{crit}$

$$\xi = \frac{C \exp[-(\zeta - \zeta_{crit}) C]}{1+C - \exp[-(\zeta - \zeta_{crit}) C]} \quad (41)$$

is obtained. In both cases

$$\zeta_{crit} = \ln \frac{\xi_i + C}{1+C} \quad (42)$$

holds. Countercurrent drying can be analyzed with the following basic equation

$$\frac{d\xi}{d\zeta} + (C^* - \xi) \dot{\nu}(\xi) = 0 \quad (43)$$

in which $C^* = C + \xi_i + \xi_f$; the subscripts denote the initial and final moisture content of the solid. Integration of Equation (43) for the region $\xi \geq 1, \zeta \leq \zeta_{crit}$ yields

$$\xi = (1-C^*) \exp(\zeta - \zeta_{crit}) + C^* \quad (44)$$

and for the region $\xi \leq 1, \zeta \geq \zeta_{crit}$

$$\xi = \frac{C^* \exp[-(\zeta - \zeta_{crit}) C^*]}{C^* - 1 + \exp[-(\zeta - \zeta_{crit}) C^*]} \quad (45)$$

The dimensionless location of the critical moisture content is given by

$$\zeta_{crit} = \ln \frac{C^* - 1}{C^* - \xi_i} \quad (46)$$

Figure 56 is an example of the variation of the moisture content ξ along the length of a dryer for cocurrent and countercurrent operation. For the calculation the values $\xi_i = 2$, $\xi_f = 0.2$, and $C = 0$ have been used. The cocurrent dryer must be 1.7 times longer than the countercurrent unit.

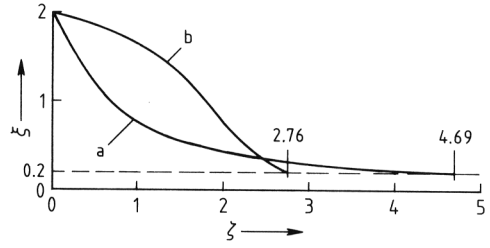


Figure 56. Dimensionless moisture content versus dimensionless location ζ in a dryer with a) Cocurrent; b) Countercurrent flow ($\xi_i = 2$, $\xi_f = 0.2$, and $C = 0$)

3.3. Heat and Driving Power Requirements

The heat consumption of dryers is determined by

- 1) the heat needed to vaporize or desorb the moisture from the solid
- 2) the heat needed to warm the solid up to the drying temperature and to heat the vapor up to its exit temperature
- 3) the heat lost to the surroundings

The heat consumption is determined from an energy and mass balance of the system. Figure 57 shows the situation for a batch dryer. Mass balance is

$$\dot{M}_g (Y_i - Y_f) = \dot{M}_s \frac{dX}{dt} \quad (47)$$

Energy balance is

$$\dot{Q}_{Heat} + \dot{W}_{Vent} = \dot{M}_g (h_f - h_i) + \dot{M}_s \frac{d(h_s + Xh_1)}{dt} + \dot{Q}_{Lost} \quad (48)$$

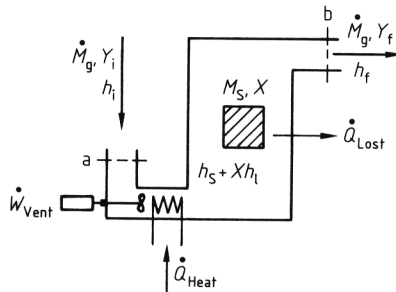


Figure 57. Schematic drawing of a batch dryer for the derivation of overall mass and energy balances a) Inlet; b) Outlet

In these equations, h_i and h_f are the entering (initial) and exiting (final) enthalpies of the moist drying agent, respectively; h_s is the enthalpy of the dry solid and h_l the enthalpy of the liquid. \dot{Q}_{heat} is the heat requirement from the heaters; \dot{W}_{vent} is the power required by the ventilation unit; and \dot{Q}_{lost} is the heat lost to the surroundings.

The corresponding equations for a continuous dryer, shown schematically in Figure 58, are

$$\dot{M}_g (Y_f - Y_i) = \dot{M}_s (X_i - X_f) \quad (49)$$

for the mass balance and

$$\dot{Q}_{\text{Heat}} + \dot{W}_{\text{Vent}} = \dot{M}_g (h_f - h_i) + \dot{M}_s [(h_{sf} - h_{si}) + (X_f h_{lf} - X_i h_{li})] + \dot{Q}_{\text{lost}} \quad (50)$$

for the energy balance.

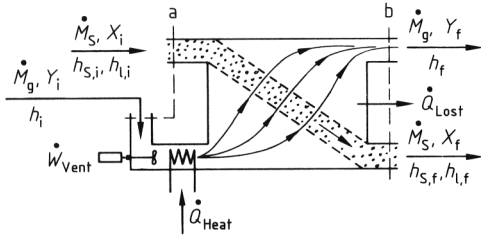


Figure 58. Schematic drawing of a continuous dryer for the derivation of overall mass and energy balances
a) Inlet; b) Outlet

Approximate values for the heat consumption of the most important types of dryers are given in Table 2.

Driving Power Consumption. Not only is energy needed as heat to the dryer, also both the solid and the drying agent must be transported. Most of the power needed to move these materials in a convection dryer is consumed by the fans or blowers. This power has already been accounted for in the overall balances of Equation (50). The vacuum pump absorbs most of the

power in a vacuum dryer. A guide to the driving power requirements of the various kinds of dryers is given in [10].

4. References

1. O. Krischer, W. Kast: *Die wissenschaftlichen Grundlagen der Trocknungstechnik*, 3rd ed., Springer, Berlin-Heidelberg-New York 1978.
2. R. B. Keey: *Drying: Principles and Practice*, Pergamon Press, Oxford 1972.
3. R. H. Perry, D. Green (eds.): *Perry's Chemical Engineer's Handbook*, 6th ed. McGraw-Hill, New York-Toronto-London, 1984, pp. 20-1–20-58.
4. P. Gummel: *Durchströmungstrocknung: Experimentelle Bestimmung und Analyse der Trocknungsgeschwindigkeit und des Druckverlustes luftdurchströmter Textilien und Papiere*, Dissertation, Karlsruhe 1977.
5. E.-U. Schlünder, N. Mollekopf: "Vacuum Contact Drying of Free Flowing Mechanically Agitated Particulate Material," *Chem. Eng. Process* **18** (1984) 93–111.
6. E.-U. Schlünder, "Heat Transfer to Packed and Stirred Beds from the Surface of Immersed Bodies," *Chem. Eng. Process.* **18** (1984) 31–53.
7. F. Thurner, E.-U. Schlünder: "Progress Towards Understanding the Drying of Porous Materials Wetted with Binary Mixtures," *Chem. Eng. Process.* **20** (1986) 9–25.
8. J. Schwarzbach, E.-U. Schlünder: "Microconvection due to Marangoni-type Instabilities in Porous Media – Effect on Pervaporation and Selective Drying," *Proc. of 3rd World Congress of Chemical Engineering*, Tokyo 1986, 560–563.
9. D. A. van Meel: "Adiabatic Convection Batch Drying with Recirculation of Air," *Chem. Eng. Sci.* **9** (1958) 36–44.
10. K. Kröll: *Trockner und Trocknungsverfahren*, 2nd ed., Springer, Berlin-Heidelberg-New York 1978.