

Dehydration

Dehydration is a major process for food preservation. The reduced weight and bulk of dehydrated products and their dry shelf stability reduces product storage and distribution costs. As dehydration techniques that produce good-quality convenience foods are developed, more dehydrated products will be commercially produced. At present, instant beverage powders, dry soup mixes, spices, and ingredients used in further processing are the major food products dehydrated.

12.1 WATER ACTIVITY

Dehydrated foods are preserved because water activity is at a level where no microbiological activity can occur and where deteriorative chemical and biochemical reaction rates are reduced to a minimum. Water activity (a_w) is measured as the equilibrium relative humidity (ERH), the per cent relative humidity (RH) of an atmosphere in contact with a product at the equilibrium water content. a_w is also the ratio of the partial pressure of water in the headspace of a product (P) to the vapor pressure of pure water (P^0) at the same temperature.

$$a_w = \text{ERH} = \frac{P}{P^0} \quad (12.1)$$

The relationship between a_w and the rate of deteriorative reactions in food is shown in Fig. 12.1. Reducing a_w below 0.7 would prevent microbiological spoilage. However, although microbial spoilage would not occur at $a_w = 0.7$, prevention of other deteriorative reactions needed to successfully preserve a food product by dehydration requires a_w to be reduced to ≈ 0.3 .

A food material may also be dehydrated only for weight or bulk reduction and finally preserved using other techniques.

12.1.1 Thermodynamic Basis for Water Activity

The first and second laws of thermodynamics are discussed in Section 4.2 –Thermodynamics. In addition to the thermodynamic variables of enthalpy (H), internal energy (E), work (W), and heat (Q) discussed under Thermodynamics in Section 4.2. Other thermodynamic variables related chemical changes will be discussed in this section.

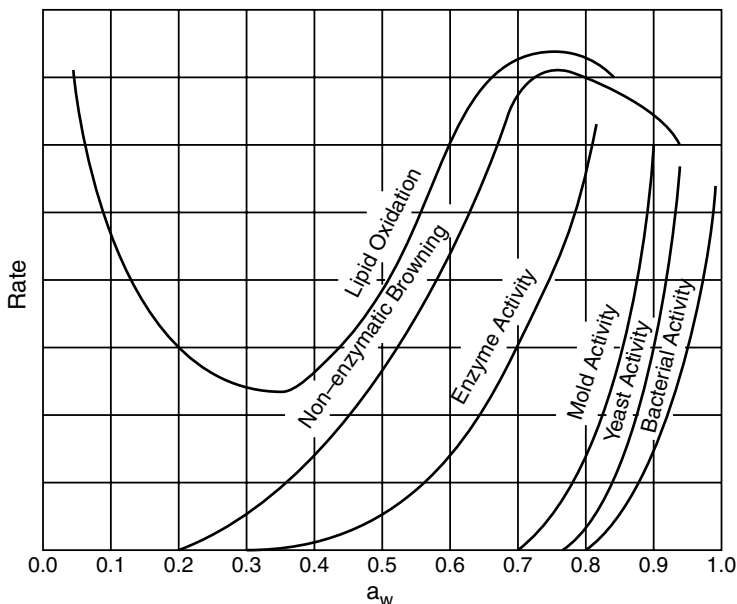


Figure 12.1 Relationship between water activity and deteriorative reaction on foods. (From Labuza T. P. et al. J. Food Sci. 37:154, 1972. Used with permission.)

F = free energy; another form of energy in a system that is different from PV work. This form of energy is responsible for chemical or electrical work and is responsible for driving chemical reactions.

$$F = H - TS \quad (12.2)$$

Φ = chemical potential. It is directly related to the free energy. In any system undergoing change, $d\Phi = dF$:

Because: $dF = dH - T dS - S dT$

and: $dH = dE + P dV + V dP$

and: $dE = T dS - P dV$

Then: $dF = V dP - S dT$;

$d\Phi = V dP - S dT$

At constant T , $d\Phi/dP = V$.

In a system in equilibrium, the chemical potential is equal in all phases. In the gas phase, the ideal gas equation for one mole of gas is $V = RT/P$. Thus:

$$d\Phi = RT d(\ln P) \quad (12.3)$$

If the vapor is nonideal, the fugacity, f , may be substituted for P . At low pressures of near ambient or in a vacuum, f is almost the same as P and the two may be interchanged in use with very little error.

Thus, the chemical potential can be measured directly by the vapor pressure of a component. The

activity of a component is defined as:

$$a = \frac{f}{f^0}$$

where f^0 is the fugacity of the pure component at the same temperature. If the component is water:

$$a_w = \frac{f}{f^0} \equiv \frac{P}{P^0} \quad (12.4)$$

The thermodynamic basis for the water activity is the chemical potential of water; its ability to participate in chemical reactions.

12.1.2 Osmotic Pressure

One consequence of reduced water activity is an increase in osmotic pressure, which interferes with food, water, and waste transport between a cell and its surroundings. The osmotic pressure is related to the activity coefficient as follows:

$$\pi = \frac{-RT}{V} \ln x\gamma \quad (12.5)$$

where π = osmotic pressure (atm); R = gas constant (82.06 mL · atm/gmole · K); γ = activity coefficient; V = molar volume = 18 mL/gmole for water; x = mole fraction of water; and T = absolute temperature. The argument of the logarithmic term in Equation (12.5) is the water activity. As the water activity approaches 1, the logarithmic term approaches zero and the osmotic pressure approaches zero.

12.1.3 Water Activity at High Moisture Contents

At high moisture contents, depression of the water vapor pressure by soluble solids is similar to vapor pressure depression by solutes in solution. The presence of insoluble solids is ignored and the solution phase determines the water activity.

For ideal solutions, the water activity is equal to the mole fraction of water, x_w .

$$a_w = x_w \quad (12.6)$$

For nonideal solutions, the activity coefficient, γ , corrects for deviation from nonideality.

$$a_w = \gamma x_w \quad (12.7)$$

The mole fraction of water, x_w , expressed in terms of weight fraction water (x'_w) and solute (x'_s) having molecular weights of 18 and M_s , respectively, is

$$x_w = \frac{\text{moles water}}{\text{moles water} + \text{moles solute}} \quad (12.8)$$

$$x_w = \frac{\frac{x'_w}{18}}{\frac{x'_w}{18} + \frac{x'_s}{M_s}}$$

Equation (12.6) is Raoult's law. In the form of Equation (12.8), Raoult's law is often cited to govern the dependence of water activity on water and solute concentration in foods. Qualitatively, Raoult's

law explains adequately the dependence of water activity on water and solute content in foods. Solutes with low molecular weights also provide larger reduction of vapor pressure per unit weight of solute than those with high molecular weights. However, a_w calculated using Equation (12.8) will differ from actual a_w because the solution phase in most foods is nonideal.

The deviation of a_w from Raoult's law is related to the heat of mixing involved in the dissolution of solute. Let ΔH_{m1} = partial molal heat of mixing, defined as the change in enthalpy of mixing with the addition of or removal of 1 mole of component 1 at constant temperature and pressure. Equation (12.9) can be derived (Perry et al., 1963) by assuming that the excess entropy of mixing is zero.

$$\overline{\Delta H_{m1}} = \frac{d(\Delta H_m)}{dN_1} = RT \ln \gamma_1 \quad (12.9)$$

Solutes in food systems exhibit negative heat of mixing with water (heat is released in mixing), and γ in Equation (12.9) is less than 1. Solutions with negative heat of mixing will have a_w less than that calculated using Raoult's law.

The activity coefficient of a regular solution can be derived using Van Laar's approximations based on van der Waal's equation of state for one mole of substance:

$$P = \frac{RT}{V - b} - \frac{a}{V^2} \quad (12.10)$$

The constant a in van der Waal's equation of state represents the magnitude of attractive forces between molecules, and the constant b represents the reduction in the volume as a result of these attractive forces. In a mixture containing N_1 and N_2 moles of components 1 and 2, respectively, a for the mixture will be determined by the constant a_1 for component 1, and a_2 for component 2. Because a is associated with attraction between molecules, the rules of permutation will give N_1 ways in which N_1 molecules can interact. If each of these interactions yield a_1 , the total yield of N_1^2 interactions will be $a_1 N_1^2$. The yield of all interactions between N_2 molecules of component 2 will be $a_2 N_2^2$. Molecules of component 1 and 2 also interact with each other and the yield of each of these interactions will be the geometric mean of a_1 and a_2 . The number of ways in which N_1 molecules of component 1 and N_2 molecules of component 2 can interact with each other (excluding interactions between like molecules) will be $2N_1 N_2$ and the yield of these interactions will be $(a_1 a_2)^{1/2} (2N_1 N_2)$. Thus, for a mixture, the van der Waal's constant a can be expressed in terms of the constants of the components according to:

$$a = a_1 N_1^2 + a_2 N_2^2 + 2 N_1 N_2 (a_1 a_2)^{1/2} \quad (12.11)$$

Constant b is associated with the volume of each molecule; therefore, b for a mixture can be expressed in terms of b_1 and b_2 is

$$b = b_1 N_1 + b_2 N_2 \quad (12.12)$$

Van Laar's first approximation assumes the ratio a/b to be the internal energy of the mixture that approximates the heat of vaporization. Furthermore, in solutions, the volume changes on mixing are small such that internal energy, E , and enthalpy, H , are equivalent. The heat of mixing will be the difference between the sum of the internal energies of pure component 1 and pure component 2 and the internal energy of the mixture.

$$-\Delta H_m = E_1 + E_2 - E_{12} \quad (12.13)$$

E_1 is a_1/b_1 , E_2 is a_2/b_2 , and E_{12} is a/b for the mixture determined using Equations (12.11) and (12.12). Equation (12.13) becomes:

$$-\Delta H_m = \frac{a_1}{b_1} + \frac{a_2}{b_2} - \frac{a_1 N_1^2 + a_2 N_2^2 + 2 N_1 N_2 (a_1 a_2)^{1/2}}{N_1 b_1 + N_2 b_2}$$

Simplifying:

$$-\Delta H_m = \frac{N_1 N_2 b_1 b_2}{N_1 b_1 + N_2 b_2} \left[\frac{a_1^{1/2}}{b_1} - \frac{a_2^{1/2}}{b_2} \right]^2$$

If the value of b for the two components are equal:

$$-\Delta H_m = \frac{N_1 N_2}{(N_1 + N_2)b} (a_1^{1/2} - a_2^{1/2})^2 \quad (12.14)$$

The partial molal heat of mixing can be determined by differentiating Equation (12.14) with respect to N_1 , keeping N_2 constant.

$$\overline{\Delta H_{m1}} = \frac{-d\Delta H_m}{dN_1} = \frac{N_2 (a_1^{1/2} - a_2^{1/2})^2}{b} \frac{d}{dN_1} \left[\frac{N_1}{N_1 + N_2} \right] = \frac{N_2 (a_1^{1/2} - a_2^{1/2})}{b} \left[\frac{N_2}{(N_1 + N_2)^2} \right]$$

Because a_1 , a_2 , and b are all constants, $k' = \frac{a_1^{1/2} - a_2^{1/2}}{b}$ and:

$$-\overline{\Delta H_m} = k' \left[\frac{N_2}{N_1 + N_2} \right]^2 = k = x_2^2 \quad (12.15)$$

Combining Equations (12.9) and (12.15):

$$RT \ln \gamma_1 = -k' x_2^2 \quad (12.16)$$

Because from Equation (12.7), $\gamma_w = a_w/x_w$, and in a two component system, $x_2 = 1 - x_w$. At constant temperature, Equation (12.16) can be written as:

$$\log \frac{a_w}{x_w} = -k(1 - x_w)^2 \quad (12.17)$$

Equation (12.17) shows that a plot of $\log a_w/x_w$ against $(1 - x_w)^2$ will be linear with a negative slope. Equation (12.17) has been used successfully by Norrish to predict the water activity of sugar solutions. Values of the constant k in Equation (12.17) for various solutes are shown in Table 12.1.

Example 12.1. Calculate the water activity of a 50% sucrose solution.

Solution:

From Table 12.1, the k value for sucrose is 2.7. Sucrose has a molecular weight of 342. The mole fraction of water is

$$x_w = \frac{50/18}{50/18 + 50/342} = 0.95$$

Using Equation (12.17):

$$\log a_w = \log x_w - 2.7(1 - x_w)^2 = \log 0.95 - 2.7(0.05)^2$$

$$a_w = 0.935$$

Table 12.1 Values of the Constant k for Various Solutes in Norrish's Equation for Water Activity of Solutions.

Sucrose	2,7
Glucose	0,7
Fructose	0.7
Invert sugars	0,7
Sorbitol	0.85
Glycerol	0.38
Propylene glycol	−0.12
Nacl	15.8($x_2 < 0.02$) 7.9($x_2 > 0.02$)
Citric acid	6.17
d-Tartaric acid	4.68
Malic acid	1.82
Lactic acid	−1.59

Sources: Norrish, R. S., *J. Food Technol.* 1:25, 1996; Toledo, R. T., *Proc. Meat. Int Res. Conf*, 1973; Chuang, L., M.S. thesis, University of Georgia, 1974; Chirife, J., and Ferro-Fontain, C., *J. Food Sci.* 45:802, 1980.

12.1.3.1 Gibbs-Duhem Equation

The chemical potential is a partial molal quantity that can be represented as the change in the free energy with a change in the number of moles of that component, all other conditions being maintained constant. $\Phi_1 = (dF/dN_1)$

$$dF = \left(\frac{dF}{dN_1} \right) dN_1 + \left(\frac{dF}{dN_2} \right) dN_2 = \mu_1 dN_1 + \mu_2 dN_2$$

But:

$$F = \Phi_1 N_1 + \Phi_2 N_2$$

$$dF = \Phi_1 dN_1 + N_1 d\Phi_1 + \Phi_2 dN_2 + N_2 d\Phi_2$$

and:

$$N_1 d\Phi_1 + N_2 d\Phi_2 = 0 \quad (12.18)$$

Equation (12.18) and similar expressions in Equations (12.19) and (12.20) are different forms of the Gibbs-Duhem equation.

$$x_1 \left(\frac{d \ln a_1}{dx_1} \right) + x_2 \left(\frac{d \ln a_2}{dx_1} \right) = 0 \quad (12.19)$$

or:

$$x_1 d \ln a_1 + x_2 d \ln a_2 = 0 \quad (12.20)$$

Let $(a_w)^0$ represent the activity of water in a system with only one solute and water in the mixture. Integration of Equation (12.20) gives

$$\ln(a_w)^0 = - \int \left(\frac{x_2}{x_1} \right) d \ln(a_2)$$

In a multicomponent system involving two solutes:

$$\begin{aligned} d \ln a_w &= - \left(\frac{x_2}{x_1} \right) d \ln a_2 - \left(\frac{x_3}{x_1} \right) d \ln a_3 \\ \ln a_w &= - \int \left(\frac{x_2}{x_1} \right) d \ln a_2 - \int \left(\frac{x_3}{x_1} \right) d \ln a_3 \\ a_w &= (a_w)_2^0 (a_w)_3^0 \end{aligned} \quad (12.21)$$

The water activity of a mixture involving several components can be determined from the product of the water activity of each component separately if all the water present in the mixture is mixed with individual components. Equation (12.21) was derived by Ross (Food Technol. 3:26, 1975).

Example 12.2. Calculate the water activity of a fruit preserve containing 65% soluble solids, 2% insoluble solids, and the rest water. The soluble solids may be assumed to be 50% hexose sugars and 50% sucrose.

Solution:

Basis: 100 g of fruit preserve.

$$\text{g hexose sugars} = 65(0.5) = 32.5 \text{ g}$$

$$\text{g sucrose} = 65(0.5) = 32.5 \text{ g}$$

$$\text{g water} = 33 \text{ g}$$

Consider sucrose dissolves in all of the water present.

$$x_s = \frac{32.5/342}{33/18 + 32.5/342} = 0.0492$$

$$x_w = 1 - 0.0492 = 0.9507$$

Using Equation (12.17) and a k value of 2.7 for sucrose:

$$\log(a_{wl})^0 = \log 0.9507 - 2.7(0.0492)^2$$

$$(a_{wl})^0 = 0.9365$$

Consider that hexose dissolves in all of the water present.

$$x_i = \frac{32.5/180}{32.5/180 + 33/18} = 0.0896$$

$$x_w = 1 - 0.0896 = 0.9103$$

Using Equation (12.17) and a k value for hexose of 0.7:

$$\log(a_{w2})^0 = \log 0.9103 - 0.7(0.0896)^2$$

$$(a_{w2})^0 = 0.8986$$

Using Equation (12.21), the a_w of the mixture is

$$a_w = (a_{w1})^0 (a_{w2})^0 = 0.9365 (0.8986) = 0.841$$

12.1.3.2 Other Equations for Calculating Water Activity

12.1.3.2.1 Bromley's Equation. For salts and other electrolytes, Bromley's equation (Bromley AIChE J. 19:313, 1973) accounts for ionic dissociation and nonideality.

$$a_w = \exp(-0.0183 m_i \phi) \quad (12.22)$$

where ϕ = osmotic coefficient, m_i = moles of ionic species i per kilogram of solvent, $m_i = I \cdot m$, where I = number of ionized species per mole and m = molality. The osmotic coefficient, ϕ , is calculated using Equation (12.23).

$$\phi = 1 + 2.303[F_1 + (0.06 + 0.6B)F_2 + 0.5BI] \quad (12.23)$$

The parameter F_1 in Equation (12.23) is calculated using Equation (12.24).

$$F_1 = F_{id}[-0.017zI^{0.5}] \quad (12.24)$$

The parameter F_{id} in Equation (12.24) is calculated using Equation (12.25).

$$F_{id} = 3I^{-1.5} \left[1 + I^{0.5} - \frac{1}{1 + I^{0.5}} - 2 \ln(1 + I^{0.5}) \right] \quad (12.25)$$

The parameter F_2 in Equation (12.23) is calculated using Equation (12.26).

$$F_2 = \frac{z}{aI} \left[\frac{1 + 2aI}{(1 + aI)^2} - \frac{\ln(1 + aI)}{aI} \right] \quad (12.26)$$

The parameter I is the ionic strength, evaluated as half the sum of the product of the molality of dissociated ions and the square of their charge; for example, for $MgCl_2$, $I = 0.5 [m(2)^2 + 2m(-1)^2] = 3m$; B and a are constants for each salt obtained from a regression of activity coefficient data against ionic strength. A comprehensive listing of a and B values for different salts is given by Bromley (1973). Chirife and Ferro-Fontan (J. Food Sci. 45:802, 1980) reported a value of B for sodium lactate of 0.050 kg/gmol. z is the charge number, the ratio of the sum of the product of the number of ions and its charge to the stoichiometric number of ions; for example, for $MgCl_2$, $z = [1(2) + 2(1)]/3 = 4/3 = 1.333$. For $NaCl$, KCl , sodium acetate and salts with monovalent cation and anion, $z = [1(1) + 1(1)]/2 = 1.0$

The values of the parameters z , I , B , and a for various salts are as follows:

For $NaCl$: $z = 1$; $I = m$; $B = 0.0574$; $a = 1.5$

For KCl : $z = 1$; $I = m$; $B = 0.0240$; $a = 1.5$

For KNO_3 : $z = 1$; $I = m$; $B = -0.0862$; $a = 1.5$

For $MgCl_2$: $z = 1.33$; $I = 3m$; $B = 0.01129$; $a = 1.153$

12.1.3.2.2 Lang-Steinberg Equation. This equation (J. Food Sci. 46:670, 1981) is useful for mixtures of solids, where there are no solute-insoluble solids interaction. The moisture content of each component X_i was considered to be linear when plotted against $\log(1 - a_{wi})$, with a slope b_i and intercept a_i . a_{wi} is the water activity of component i at moisture content X_i . If X is the equilibrium

moisture content of the mixture, g water/g dry matter, and S is the total mass of dry matter in the mixture, the a_w of the mixture can be calculated from the mass of dry matter in each component, S_i as follows:

$$\log(1 - a_w) = \frac{XS - \sum(a_i S_i)}{\sum(b_i X_i)} \quad (12.27)$$

12.1.4 Water Activity at Low Moisture Contents

If the water content of a food is plotted against the water activity at constant temperature, a sigmoid curve ally results. The curve is known as the sorption isotherm for that product. Figure 12.2 shows a sorption isotherm for raw beef at 25°C.

The sorption isotherm can be subdivided into three zones, each zone representing a different mechanism for water sorption. In zone C, the influence of insoluble solids on the a_w is negligible. a_w is dependent on the solute and water content of the solution phase and can be calculated using Equations (12.17) and (12.21).

In zone B, the influence of insoluble solids on a_w becomes significant. The sorption isotherm flattens out, and very small changes in moisture content are reflected by very large changes in the water activity. In this zone, water is held in the solid matrix by capillary condensation and multilayer adsorption. Some of the solutes may also be in the form of hydrates. Some of the water may still be in the liquid phase, but its mobility is considerably restricted because of attractive forces with the solid phase. The quantity of water present in the material that would not freeze at the normal freezing point usually is within this zone.

Zone A represents adsorption of water on the surface of solid particles. None of the water is in the liquid phase anymore. The heat of vaporization of water in this zone is higher than the heat of

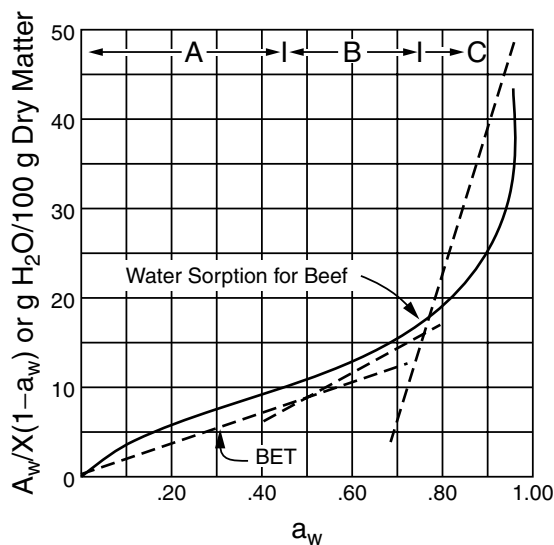


Figure 12.2 Sorption isotherm of dried raw beef at 25°C, showing the three segments of the BET plot.

vaporization of pure water because both heat of vaporization and heat of adsorption must be supplied to remove the water molecules from the solid surface.

The relationship between water activity and moisture content in zone A is best described by the Brunauer-Emmett-Teller (BET) equation. If x is the moisture content in g H_2O /g dry matter,

$$\frac{a_w}{x(1 - a_w)} = \frac{1}{x_m C} + \frac{C - 1}{x_m C}(a_w) \quad (12.28)$$

x_m in Equation (12.28) is the mass fraction of water in the material equivalent to a unimolecular layer of water covering the surface of each particle. C is a constant at constant temperature and is related to the heat of adsorption of water on the particles. C is temperature dependent.

A plot of $a_w/x(1 - a_w)$ against a_w is called the BET plot. The plot would be linear and the slope and intercept of the line can be used to determine the constant x_m , the moisture content at which the water molecules coat the surface of the solid particles in a monomolecular layer.

The region of maximum stability for a food product is usually in zone B in Fig. 12.2. When the moisture content in the product drops to a level insufficient to cover the solid molecules in a monomolecular layer, the rate of lipid oxidation increases. Determining the moisture content for maximum shelf stability of a dehydrated material would involve determining the sorption isotherm and calculating the value of x_m in Equation (12.28) from a BET plot.

The dashed lines in Fig. 12.2 are BET plots of the sorption data for raw beef. The line in zone A represents monomolecular adsorption and will be used for calculating x_m . The slope and intercept of the line are 13.7 and 0.98, respectively. From Equation (12.28), the intercept is $1/x_m C$. $x_m C = 1/0.98 = 1.02$. The slope is $(C - 1)/x_m C$.

$$\begin{aligned} \frac{C - 1}{1.02} &= 13.7 \\ C &= 14.974 \\ x_m &= \frac{1.02}{14.974} = 0.068 \text{ gH}_2\text{O/g dry matter} \end{aligned}$$

12.1.4.1 The GAB (Guggenheim-Anderson-de Boer) Equation

This equation gives a better fit than the BET over a wider range of moisture contents. Let X = moisture content on a dry solids basis, and X_m = the moisture content on a dry basis, equivalent to a monomolecular layer of water.

Then:

$$X = \frac{X_m C k a_w}{(1 - k a_w)(1 - k a_w + C k a_w)} \quad (12.29)$$

The GAB equation is a three-parameter equation with k , C , and X_m as constants. C and X_m have similar significance as in the BET equation. k is a third parameter that corrects for the difference in properties of adsorbed water relative to liquid water and permits the GAB equation to hold over a wider range of moisture content than the BET. Both k and C are temperature dependent.

Evaluation of X_m using Equation (12.29) is more precise than that using the BET equation, because the fit of Equation (12.29) to the data extends over a wide range of moisture contents. The narrow range of moisture contents to which Equation (12.28) fits often presents some problems in the determination of X_m using the BET equation, particularly when data points are not close enough at the lower moisture contents.

Rearranging Equation (12.29) by taking the reciprocal:

$$\frac{1}{X} = \frac{1}{X_m} \left[\frac{1}{C k a_w} - \frac{1}{C} \right] [1 - k a_w + C k a_w]$$

$$\frac{a_w}{X} = \left[\frac{k}{X_m C} \right] (1 - C) a_w^2 + \left[\frac{C - 2}{X_m C} \right] a_w + \frac{1}{X_m C k}$$

Thus, a polynomial nonlinear regression of (a_w/X) against (a_w) will give values for α , the coefficient of the quadratic term, β the coefficient of the linear term, γ the intercept.

$$\beta = \frac{C - 2}{X_m C}; \quad \alpha = \left[\frac{k}{X_m C} \right] [1 - C]; \quad \gamma = \frac{1}{X_m C k}$$

These three equations can be used to evaluate C , k , and X_m .

Multiple nonlinear regression techniques must be used to fit and evaluate the parameters for this equation from moisture-water activity data.

Example 12.3. Fitting GAB Equation to Sorption Isotherm Data: The following data (a_w , X) was obtained for the sorption isotherm of potatoes at 25°C. X is the moisture content in g water/g dry matter. Calculate the GAB parameters, X_m , C , and k . Data: (0.112, 0.035), (0.201, 0.057), (0.327, 0.08), (0.438, 0.105), (0.529, 0.13), (0.577, 0.145), (0.708, 0.19), (0.753, 0.204), (0.843, 0.27), (0.903, 0.37).

Solution:

Use Excel to calculate a_w/X and tabulate against a_w . The following are the results:

Independent variable (a_w)	Dependent variable (a_w/X)
0.112	3.2
0.201	3.52
.327	4.09
.438	4.17
.529	4.07
.577	3.98
.708	3.73
.753	3.69
.843	3.12
.903	2.44

Perform a nonlinear regression (using a statistical software package, e.g., Systat) to fit the following model to the data:

$$a_w/X = \alpha(a_w)^2 + \beta(a_w) + \gamma$$

Regression results: $\alpha = -8.24$; $\beta = 7.69$; $\gamma = 2.39$. The r^2 value of the regression = 0.969 indicating a good fit throughout the full data set. Values of k , C , and X_m can then be calculated.

Solving for X_m in the expressions for α , β , and γ in the GAB equation:

$$X_m = [k(1 - C)/C\alpha] = [(C - 2)/C\beta] = 1/Ck\gamma$$

Solving the equalities will result in two equations:

$$k^2(1 - C) = \alpha/\gamma; C = 2 + \beta/\gamma k$$

Substituting C: $k^2(1 - 2 - \beta/\gamma k) = \alpha/\gamma$; $k^2 + (\beta/\gamma)k + \alpha/\gamma = 0$ Using the quadratic equation and taking the positive root: $k = 0.848$; $C = 2 + \beta/\gamma k = 5.79$; $X_m = 1/Ck\gamma = 0.0852$.

12.1.4.2 Other Equations for Sorption Isotherms of Foods

Other equations that have been used to fit the sorption isotherms of foods are Equation (12.30) to (12.39). Iglesias and Chirife (1982) fitted sorption isotherms to these equations and reported the best-fitting equations with the corresponding value of the equation parameters. Halsey's (Eq. 12.34), Henderson's (Eq. 12.35), Oswin's (Eq. 12.38), and Smith's (Eq. 12.39) was reported to fit more water sorption/desorption data among these equations.

Caurie equation:

$$\ln(1 - X) = A - r \ln(a_w) \quad (12.30)$$

X = moisture content dry basis

A and r are constants obtained from the regression equation for $\ln(1 - X)$ versus $\ln(a_w)$.

Chen equation:

$$a_w = \exp[-K \exp(-bX)] \quad (12.31)$$

$$\ln[-\ln(a_w)] = \ln(K) - bX$$

K and b are constants obtained from a linear regression of $\ln[-\ln(a_w)]$ versus X.

Chong-Pfost equation:

$$\ln(a_w) = \frac{-A}{T} \exp(-BX) \quad (12.32)$$

A and B are constants.

Day and Nelson equation:

$$a_w = 1 - \exp[P_1 T^{P_2} X^{P_3}] \quad (12.33)$$

P_1, P_2, P_3 are constants; T = absolute temperature.

Halsey equation:

$$a_w = \exp\left[\frac{-A}{T} \theta^b\right] \quad (12.34)$$

$\theta = X/X_m$; and a and b are constants.

Henderson equation:

$$1 - a_w = \exp[-aX^b] \quad (12.35)$$

a and b are constants.

Iglesias and Chirife equation:

$$X = B_1 \left[\frac{a_w}{1 - a_w} \right] + B_2 \quad (12.36)$$

B_1 and B_2 are constants.

Kuhn equation:

$$X = \frac{A}{\ln(a_w)} + B \quad (12.37)$$

Oswin equation:

$$X = A \left[\frac{a_w}{1 - a_w} \right] + B \quad (12.38)$$

Smith equation:

$$X = A - B \ln(1 - a_w) \quad (12.39)$$

These equations are empirical and are usually used when the fit to the GAB equation is not very good. The advantage of the GAB and BET equations is that they are based on physical adsorption phenomena, therefore the parameters have physical meaning. Expressing sorption isotherms in equation form avoids the need for graphs in representing water activity of foods as a function of moisture content. These equations will also facilitate the calculation of equilibrium moisture content and water activity in individual particulate component when mixing particulate solids with different water activities.

12.2 MASS TRANSFER

During dehydration, water is vaporized only from the surface. The transfer of water vapor from the wet surface to a stream of moving air is analogous to convection heat transfer, therefore a mass transfer coefficient is used. Moisture flux is proportional to the driving force, which is the difference in vapor pressure on the surface and the vapor pressure of water in air surrounding the surface. At the same time that water is removed from the surface, water diffuses from the interior of a solid toward the surface. The latter is a general form of diffusion that is analogous to conduction heat transfer. The differential equations for conduction also applies for diffusion, but a mass diffusivity is used in place of the thermal diffusivity.

12.2.1 Mass Diffusion

For an infinite slab, Equation (7.89) in the section “The Infinite Slab,” Chapter 7, can be used for the dimensionless moisture change with time. Expressing this equations in terms of moisture content and mass diffusivity:

$$\theta = \frac{X - X_m}{X_0 - X_m}$$

where X is moisture content at any time, dry matter basis (kg water/kg dry matter), X_0 is initial moisture content, and X_m is equilibrium moisture content. The equation for moisture content at any point y in the solid measured from the center, at any time t , when the moisture content X was originally uniform at X_0 is

$$\theta = 2 \sum_{n=0}^{\infty} \frac{(-1)^n}{(n + 0.5)\pi} \left[\left(e^{-(n+0.5)^2 \pi^2 D_m \frac{t}{L^2}} \right) \left(\cos \left(\frac{(n + 0.5)\pi y}{L} \right) \right) \right] \quad (12.40)$$

Assumptions used in the derivation of this equation are constant diffusivity, and constant surface moisture at the moisture content in equilibrium with the drying air, during the process. The value of X_m is determined from the sorption isotherm of the solid at a_w = decimal equivalent of per cent relative humidity of the drying air.

During the early stages of dehydration, moisture is transferred and moves from the center toward the surface by capillary action. This mechanism is more rapid than diffusion, and rate of surface evaporation controls the rate of drying. However, in the later stages of drying, diffusion controls the rate of moisture migration within the solid. Diffusivity may be constant if cells do not collapse and pack together. Firm solids such as grain may exhibit constant diffusivity, but high-moisture products such as fruits and vegetables may exhibit variable diffusivity with moisture content depending on the physical changes that occur as water is removed.

The mass diffusivity D_m has the same units as thermal diffusivity and can be used directly to substitute for α in the heat transfer equations. Of interest in dehydration processes is the average moisture content in the slab at any time during the drying process. Let W and Z represent the width and length of the slab. The total moisture in the slab is

$$\text{Total moisture} = \rho W Z \int_0^L X dy$$

The mean moisture \bar{X} = total moisture/total mass:

$$\bar{X} = \frac{1}{L} \int_0^L X dy$$

The dimensionless moisture ratio $\bar{\theta}$ based on the average moisture content is:

$$\bar{\theta} = \frac{\bar{X} - X_m}{X_0 - X_m}$$

Substituting the expression for X obtained from Equation (12.40) into the above integral and integrating:

$$\bar{\theta} = 2 \sum_{n=0}^{\infty} \left[\frac{(-1)^n}{(n+0.5)^2 \pi^2} [e]^{-(n+0.5)^2 \pi^2 D_m \frac{t}{L^2}} \right] [\sin(n+0.5)\pi] \quad (12.41)$$

The squared term in the denominator of Equation (12.41) results from the integration of the cosine function of Equation (12.40).

Table 12.2 shows the values of the dimensionless mean moisture ratio $\bar{\theta}$ as a function of $(D_m t)/L^2$. L is the half thickness of the slab. For three dimensional diffusion, $\bar{\theta}_{L1}$ is obtained for $(D_m t/L_1^2)$, $\bar{\theta}_{L2}$ is obtained for $(D_m t/L_2^2)$, and $\bar{\theta}_{L3}$ is obtained for $(D_m t/L_3^2)$. The composite $\bar{\theta}$ is the product of $\bar{\theta}_{L1}$, $\bar{\theta}_{L2}$ and $\bar{\theta}_{L3}$.

When $(D_m t)/L^2 > 0.1$, the first 3 terms in the series in Equation (12.41) is adequate for series convergence. Taking logarithms of both sides of Equation (12.41):

$$\log(\bar{\theta}) = \frac{\pi^2 D_m}{L^2} t \log(e) + B$$

$$B = \log(2) + \log A_1(e)^{0.25} + \log A_2(e)^{2.25} + \log A_3(e)^{6.25}$$

$$A_1, A_2, A_3 = \frac{(-1)^n \sin[(n+0.5)\pi]}{(n+0.5)^2 \pi^2} \quad \text{for } n = 0, 1, 2 \quad (12.42)$$

Equation (12.42) shows that a semi-log plot of the dimensionless mean moisture ratio against time of drying will be linear if D_m is constant. The mass diffusivity, D_m , can be calculated from the slope.

Table 12.2 Dimensionless mean moisture ratio as a function of D_{mt}/L^2

$\frac{D_{mt}}{L^2}$	$\bar{\theta}$	$\frac{D_{mt}}{L^2}$	$\bar{\theta}$	$\frac{D_{mt}}{L^2}$	$\bar{\theta}$
0	1.0000	0.10	0.6432	1.10	0.0537
0.01	0.8871	0.20	0.4959	1.20	0.0411
0.02	0.8404	0.30	0.3868	1.30	0.0328
0.03	0.8045	0.40	0.3021	1.40	0.0256
0.04	0.7743	0.50	0.2360	1.50	0.0200
0.05	0.7477	0.60	0.1844	1.60	0.0156
0.06	0.7236	0.70	0.1441	1.70	0.0122
0.07	0.7014	0.80	0.1126	1.80	0.0095
0.08	0.6808	0.90	0.0879	1.90	0.0074
0.09	0.6615	1.00	0.0687	2.00	0.0058

Example 12.4. The desorption isotherm of apples was reported by Iglesias and Chirife (1982) to best fit Henderson's equation with the constants $a = 4.471$ and $b = 0.7131$. Experimental drying data for apple slices showed that when the average moisture content was 1.5 kg water/kg dry matter, the drying rate, which may be assumed to be diffusion controlled, was 8.33×10^{-4} kg water/[kg dry matter (s)]. The apple slices were 1.5 cm thick and 2.5 cm wide and were long enough to consider diffusion to occur from two dimensions. The drying air has a relative humidity of 5%.

- Calculate the mass diffusivity of water at this stage of drying.
- Calculate the drying rate and moisture content after 1 hour of drying from when the moisture content was 1.5 kg water/kg dry matter.

Solution:

- Henderson's equation will be used to calculate the equilibrium moisture content, X_m . Solving for X_m by substituting X_m for X in Henderson's equation:

$$\ln(1 - a_w) = -aX^b; \quad X_m = \left[\frac{-\ln(1 - 0.05)}{4.471} \right]^{1/0.7131}$$

$$X_m = 0.0019$$

Equation (12.42) for diffusion from two dimensions is

$$\log(\bar{\theta}) = \left[\frac{1}{(L_1)^2} + \frac{1}{(L_2)^2} \right] \pi^2 D_m \log(e)t + B \quad (12.43)$$

Differentiating Equation (12.43) with respect to t :

$$\frac{d}{dt}[\log(\bar{\theta})] = \left[\frac{1}{(L_1)^2} + \frac{1}{(L_2)^2} \right] \pi^2 D_m \log(e) \quad (12.44)$$

Differentiating the expression for $\bar{\theta}$ with respect to t :

$$\log(\bar{\theta}) = \log\left(\frac{\bar{X} - X_m}{\bar{X}_o - X_m}\right)$$

$$\frac{d}{dt}[\log(\bar{\theta})] = \frac{1}{(\bar{X} - X_m)[\ln(10)]} \frac{d\bar{X}}{dt} \quad (12.45)$$

Combining Equations (12.44) and (12.45) and solving for D_m :

$$D_m = \frac{d\bar{X}/dt}{(\bar{X} - X_m) \left[\frac{1}{(L_1)^2} + \frac{1}{(L_2)^2} \right] \pi^2} \quad (12.46)$$

Substituting known quantities:

$$D_m = \frac{8.33 \times 10^{-4}}{(1.5 - 0.0019)[(1/0.0075)^2 + (1/(0.0125)^2)] \pi^2} = 2.3302 \times 10^{-9} \text{ m}^2/\text{s}$$

(b) Solving for $D_m t/L^2$ for $t = 3600$ s:

$$L = 0.0075; (D_m t/L^2) = 0.149$$

$$L = 0.0125; (D_m t/L^2) = 0.054$$

From Table 12.2:

When $(D_m t/L^2) = 0.149$, by interpolation:

$$\bar{\theta}_{L1} = [0.6432 - (0.6432 - 0.4959)(0.049)]/0.1 = 0.571$$

When $(D_m t/L^2) = 0.054$, by interpolation:

$$\bar{\theta}_{L2} = [0.7477 - (0.7477 - 0.7236)(0.004)]/0.01 = 0.738$$

For diffusion from two directions:

$$\bar{\theta} = 0.571(0.738) = 0.4214$$

$$\bar{X} = 0.4214(1.5 - 0.019) + 0.019 = 0.633 \text{ kg water/kg dry matter}$$

The drying rate is $d\bar{X}/dt$. Using Equation (12.46):

$$\begin{aligned} \frac{d\bar{X}}{dt} &= D_m (\bar{X} - X_m) \left[\frac{1}{(L_1)^2} + \frac{1}{(L_2)^2} \right] \pi^2 \\ &= [2.330 \times 10^{-9}(0.633 - 0.0019)(\pi^2)] \left[\frac{1}{(0.0075)^2} + \frac{1}{(0.0125)^2} \right] \\ &= 0.000351 \text{ kg water}/(\text{s} \cdot \text{kg dry matter}) \end{aligned}$$

12.2.2 Mass Transfer from Surfaces to Flowing Air

When air flows over a wet surface, water is transferred from the surface to air. The equations governing rate of mass transfer is similar to that for heat transfer. By analogy, the driving force for mass transfer is a concentration difference, and the proportionality constant between the mass flux and the driving force is the mass transfer coefficient.

$$\frac{dW_w}{A dt} = k_g M_w (a_{ws} - a_{wa}) \quad (12.47)$$

where W_w is the mass of water vapor transferred from the surface to the moving air, A is the surface area exposed to air, M_w is the molecular weight of water, a_{ws} is water activity on the surface, and a_{wa} is

the water activity of the drying air. Using the dimensionless a_w difference as the driving force results in the mass transfer coefficient, k_g , having units in a general form widely used in the literature, kg moles/(m² · s).

Determination of the mass transfer coefficient is analogous to that in heat transfer, which involves the use of dimensionless groups. The equivalent of the Nusselt number in mass transfer is the Sherwood number (Sh).

$$Sh = \frac{k_g D}{D_{wm}} \quad (12.48)$$

where D is the diameter or characteristic length, and D_{wm} is the diffusivity expressed in kg mole/(m · s).

The equivalent of the Prandtl number in mass transfer is the Schmidt number expressed in either the mass diffusivity, D_{mX} in m²/s, or D_{wm} in kg mole/(m · s). Physical property terms in the Schmidt number for dehydration processes are those for air. M_a is the molecular weight of air, 29 kg/kg mole. D_m is diffusivity of water in air = 2.2×10^{-5} m²/s.

$$Sc = \frac{\mu}{\rho D_m} = \frac{\mu}{M_a D_{wm}} \quad (12.49)$$

Correlation equations for the mass transfer coefficient are similar to those for heat transfer. Typical expressions are as follows.

Gilliland and Sherwood equation:

$$Sh = 0.023 Re^{0.81} Sc^{0.44} \quad (12.50)$$

Equation (12.50) was derived for vaporization from a water film flowing down a vertical tube to air flowing upwards through the tube. The Reynolds number of flowing air ranged from 2000 to 35,000, and pressure ranged from 0.1 to 3 atm.

Colburn j factor:

$$j = \frac{k_g}{G} Sc^{0.666} = 0.023 Re^{-0.2} \quad (12.51)$$

G is the molar flux of air, kg moles/(m² · s) = PV/RT ; P = pressure in Pa; V = velocity, m/s, R = 8315 N · m / (kg mole · K); and T = absolute temperature. Equation (12.51) may be used for mass transfer into air flowing through particles in a packed bed. Equation (12.50) would be suitable for air flowing parallel to the surface of a bed of particles.

Ranz and Marshall's equation:

$$Sh = 2 + 0.6 Re^{0.5} Sc^{0.33} \quad (12.52)$$

Equation (12.52) is suitable for mass transfer from surfaces of individual particles such as in fluidized beds.

In dehydration, mass transfer is not the rate limiting mechanism, particularly at high air velocities needed to maintain low humidity in the drying air.

Example 12.5. Calculate the rate of dehydration expected from mass transfer when 1 cm. carrot cubes having a density of 1020 kg/m³ are dried in a fluidized bed with air at 2% relative humidity flowing at the rate of 12 m/s. Atmospheric pressure is 101 kPa and air temperature is 80°C. Express dehydration rate as kg/(s · kg dry matter) when moisture content is 5 kg water/kg dry matter.

Solution:

At 80°C, the viscosity of air from the *Handbook of Chemistry and Physics* is 0.0195 cP. The characteristic length of a cube may be calculated as the diameter of a sphere having the same surface area.

$$D = L(6/\pi)^{0.5} = 1.382 L$$

The mass flux is calculated using the ideal gas equation by substituting air velocity, \bar{V} , for volume:

$$G = \frac{101,000(12)(29)}{8315(353)} = 11.975 \frac{\text{kg}}{\text{m}^2 \cdot \text{s}}$$

$G = P\bar{V}M_a/RT \cdot M_a$ is the molecular weight of air, 29 kg/kg mole.

The Reynolds number is $DG/\Phi = 1.382 LG/\Phi$

$$\text{Re} = \frac{1.382(0.01)(11.975)}{0.0195(0.001)} = 8487$$

The density, ρ , is obtained using the ideal gas equation.

$$\rho = \frac{PM_a}{RT} = \frac{101,000(29)}{8315(353)} = 0.998 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Sc} = \frac{\mu}{\rho D_m} = \frac{0.0195(0.001)}{0.998(2.2 \times 10^{-5})} = 0.888$$

$$\text{Sh} = 2 + 0.6(8487)^{0.5}(0.888)^{0.33} = 55.15$$

Equation (12.49):

$$= 7.57 \times 10^{-7} \text{kgmole}/(\text{m} \cdot \text{s})$$

Equation (12.48):

$$k_g = \text{Sh} \left(\frac{D_{wm}}{D} \right)$$

$$= \frac{55.15(7.57 \times 10^{-7})}{0.01(1.382)} = 0.00302 \frac{\text{kgmole}}{\text{m}^2 \cdot \text{s}}$$

$$D_{wm} = \left(\frac{\rho D_m}{M_a} \right) = \frac{0.998(2.2 \times 10^{-5})}{29}$$

Express area as m^2/kg dry matter (DM).

$$A = \frac{6(0.01)^2}{(0.01)^3(1020)(1/6)} = 3.529 \frac{\text{m}^2}{\text{kg DM}}$$

Equation (12.47):

$$\frac{dW}{dt} = [3.529][0.00302(18)(1 - 0.02)] = 0.188 \frac{\text{kg}}{\text{s} \cdot \text{kg DM}}$$

The drying rate, based on surface mass transfer, is 0.188 kg water/(s · kg DM).

12.3 PSYCHROMETRY

12.3.1 Carrying Capacity of Gases for Vapors

The mass of any component of a gas mixture can be calculated from the partial pressure using the ideal gas equation. The ideal gas equation can be written for the whole mixture or for a single component as follows:

$$P_t V = n_t RT \quad \text{for the whole mixture}$$

or:

$$P_a V = n_a RT \quad \text{for component A,} \quad (12.53)$$

where P_a and n_a are partial pressure and number of moles of component A in the mixture, respectively. If the mixture consists only of components A and B,

$$P_t = P_a + P_b \quad (12.54)$$

For component B:

$$(P_t - P_a)(V) = n_b RT \quad (12.55)$$

Dividing Equation (12.53) by Equation (12.55):

$$\frac{P_a}{P_t - P_a} = \frac{n_a}{n_b}$$

If M_a is the molecular weight of component A and M_b is the molecular weight of component B, the mass ratio of the two components can be determined from the partial pressure as follows:

$$\frac{W_b}{W_a} = \frac{n_b M_b}{n_a M_a} = \frac{P_b}{(P_t - P_b)} \frac{M_b}{M_a} \quad (12.56)$$

If component A is water and component B is air, the mass ratio is known as the “humidity” or “absolute humidity.” If P_a is equal to the vapor pressure of water at the given temperature of the air, the mass ratio of components A and B is the saturation humidity. If P_a is less than the vapor pressure, the ratio P_a/P_s , where P_s is the saturation partial pressure or the vapor pressure, is the saturation ratio. This ratio expressed as a percentage is also known as the “relative humidity.”

Example 12.6. Dry air is passed through a bed of solids at the rate of $1 \text{ m}^3/\text{s}$ at 30°C and 1 atm. If the solids have an equilibrium relative humidity of 80%, and assuming that the bed is deep enough such that equilibrium is attained between the solids and the air before the air leaves the bed, determine the amount of water removed from the bed per hour. Use 29 for the average molecular weight of air. Atmospheric pressure is 101.325 kPa.

Solution:

At equilibrium, the partial pressure of water in the air should be 80% of the vapor pressure of water at 30°C . From Appendix Table A.4, the vapor pressure of water at 30°C is 4.2415 kPa. The partial pressure of water in the air is 80% of 4.215 or 3.393 kPa. The molecular weight of water is 18.

The absolute humidity can be calculated using Equation (12.56):

$$\frac{W_w}{W_a} = \frac{3.394}{(101.325 - 3.394)} \frac{18}{29} = 0.0215 \frac{\text{kg water}}{\text{kg dry air}}$$

In order to calculate the total amount of water removed in one hour, the total amount of dry air that passed through the bed per hour must be calculated.

For the dry air component:

$$PV = nRT = \frac{W_a}{M_a} RT$$

$$W_a = \frac{P_a M_a}{RT} V$$

Substituting values for P_b , M_b , R , and T and using $R = 8315 \text{ N} \cdot \text{m}/(\text{kg mole}) (\text{K})$:

$$W_a = \frac{(101,325 \text{ N} \cdot \text{m}^{-2})(29)(\text{kg})(\text{kg mole})^{-1}}{8315 \text{ N} \cdot \text{m}(\text{kg mole})^{-1}(\text{K})^{-1}(30 + 273)\text{K}} \left[1 \frac{\text{m}^3}{\text{s}} \right] = 1.166 \text{ kg/s of dry air.}$$

The weight of water removed per hour is

$$W_w = 1.166 \frac{\text{kg dry air}}{\text{s}} 0.0215 \frac{\text{kg water}}{\text{kg dry air}} \frac{3600 \text{ s}}{\text{h}} = 90.24 \text{ kg/h of water}$$

12.3.2 The Psychrometric Chart

Psychrometry is a study of the behavior of mixtures of air and water. In the preceding section, the determination of saturation humidities from the vapor pressure and the determination of the humidity from the partial pressure of water in air was discussed. A graph of humidity as a function of temperature at varying degrees of saturation forms the main body of a psychrometric chart. For processes that involve loss or gain of moisture by air at room temperature, the psychrometric chart is very useful for determining changes in temperature and humidity.

Another main feature of a psychrometric chart is the wet bulb temperature. When a thermometer is fitted with a wet sock at the bulb and placed in a stream of air, evaporation of water from the sock cools the bulb to a temperature lower than what would register if the bulb is dry. The difference is known as the wet bulb depression and is a function of the relative humidity of the air. The more humid air allows less vaporization, thus resulting in a lower wet bulb depression.

The various quantities that can be determined from a psychrometric chart are as follows:

Humidity (absolute humidity) (H): the mass ratio of water to dry air in the mixture.

Relative humidity (% RH): the ratio of partial pressure of water in the air to the vapor pressure of water, expressed in a percentage.

Dry bulb temperature (T_{db}): actual air temperature measured using a dry temperature sensing element.

Wet bulb temperature (T_{wb}): air temperature measured using a wet sensing element that allows cooling by evaporation of water.

Dew point (T_{dp}): temperature to which a given air-water mixture needs to be cooled to start condensation of water. At the dew point, the air is saturated with water vapor. The dew point is also that temperature where the vapor pressure of water equals the partial pressure of water in the air.

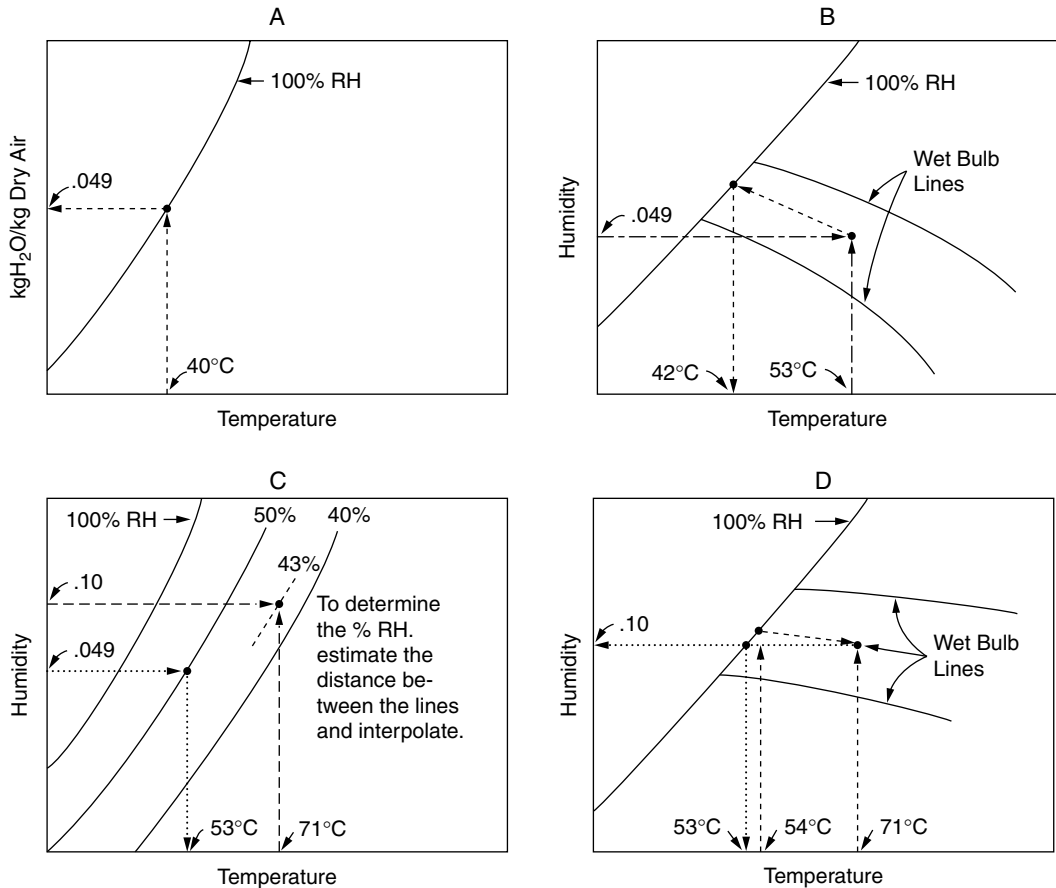


Figure 12.3 Diagram showing the use of a psychrometric chart for determining properties of air-water mixtures. (Courtesy of Proctor and Schwartz, Inc. Copyrighted by Proctor and Schwartz, Inc.)

A psychrometric chart has its axes temperature on the abscissa and humidity on the ordinate. Two parameters are necessary to establish a point on the chart that represents the condition of air. These parameters could be any two from relative humidity, dry bulb temperature, wet bulb temperature, and dew point or absolute humidity. Dew point and absolute humidity are not independent, knowing one establishes the other.

Psychrometric charts in metric and English units are in the Appendix (Fig. A5 and A7). Figure 12.3 is a diagrammatic representation of how quantities are read from a psychrometric chart. Figure 12.3A shows how dew point is determined from the humidity. Figure 12.3B shows how the wet bulb temperature is determined from the humidity and the dry bulb temperature. Figure 12.3C shows how the percentage of relative humidity is determined knowing the dry bulb and the humidity, and how dry bulb temperature is determined from humidity and % relative humidity. Figure 12.3D shows how humidity and dew point are determined from the wet and dry bulb temperatures.

Example 12.7. Air has a dew point of 40°C and has a relative humidity of 50%. Determine (a) the absolute humidity, (b) the wet bulb temperature, and (c) the dry bulb temperature.

Solution:

Using a psychrometric chart, draw a vertical line through $T = 40^{\circ}$. At the intersection with the line representing 100% relative humidity (% RH), draw a horizontal line and read the absolute humidity represented by this horizontal line at the abscissa (see Fig. 12.3A). (a) $H = 0.049$ kg water/kg dry air.

Extend the horizontal line representing the humidity until it intersects the diagonal line representing 50% RH. Draw a vertical line through this intersection and read the dry bulb temperature representing this vertical line at the abscissa (see Fig. 12.3C). (b) Dry bulb temperature = 53°C .

From the point represented by $H = 0.049$ and $T_{\text{db}} = 53^{\circ}\text{C}$, draw a line that parallels the wet bulb lines. Project this line to its intersection with the 100% RH line. Draw a vertical line at this intersection, project to the abscissa and read the wet bulb temperature at the abscissa (see Fig. 12.3B). (c) $T_{\text{wb}} = 42^{\circ}\text{C}$.

Example 12.8. Air in a smokehouse has a wet bulb temperature of 54°C and a dry bulb temperature of 71°C . Determine (a) the humidity, (b) the dew point, and (c) the percentage of relative humidity.

Solution:

Draw vertical lines through $T = 54^{\circ}\text{C}$ and the line representing 100% RH, draw a line that parallels the wet bulb lines. From the intersection of this drawn wet bulb line with the vertical line representing $T = 71^{\circ}\text{C}$, draw a horizontal line and project to the abscissa. Read the humidity represented by this horizontal line (see Fig. 12.3D). (a) $H = 0.1$ kg water/kg dry air.

From the intersection of the horizontal line representing $H = 0.1$ with the 100% RH line, draw a vertical line and connect to the abscissa. (b) $T_{\text{dp}} = 53^{\circ}\text{C}$.

From the intersection of the line representing $T = 71^{\circ}\text{C}$ and that representing $H = 0.1$, interpolate between the diagonal lines representing 40% and 50% RH and estimate the % RH (see Fig. 12.3B). (c) % RH = 43%.

12.3.3 Use of Psychrometric Chart to Follow Changes in the Properties of Air-Water Mixtures Through a Process

Figure 12.4 shows the path of a process on a psychrometric chart for heating, cooling and adiabatic humidification.

When the temperature of air is increased at constant pressure and there is no water added or removed from the air, the process is a constant humidity process. T_{db} increases, T_{wb} also increases, but % RH decreases. The process is represented by A in Fig. 12.4. When the temperature of air is decreased above the dew point, the process is a constant humidity process represented by B in Fig. 12.4. Both T_{db} and T_{wb} decrease and % RH increases. Cooling below the dew point results in condensation of water and humidity drops. The % RH remains at 100% and the temperature and humidity drops following the line representing 100% RH. This is shown by C in Fig. 12.4.

Adiabatic humidification is a process where water is picked up by air and the heat required to vaporize the added water comes from the sensible heat loss that results from a reduction of the temperature of the air. The path traced by the temperature and humidity of the air is represented by D in Fig. 12.4, and this path parallels the wet bulb lines. The wet bulb temperature of the air remains constant, humidity and % RH increases and T_{db} decreases.

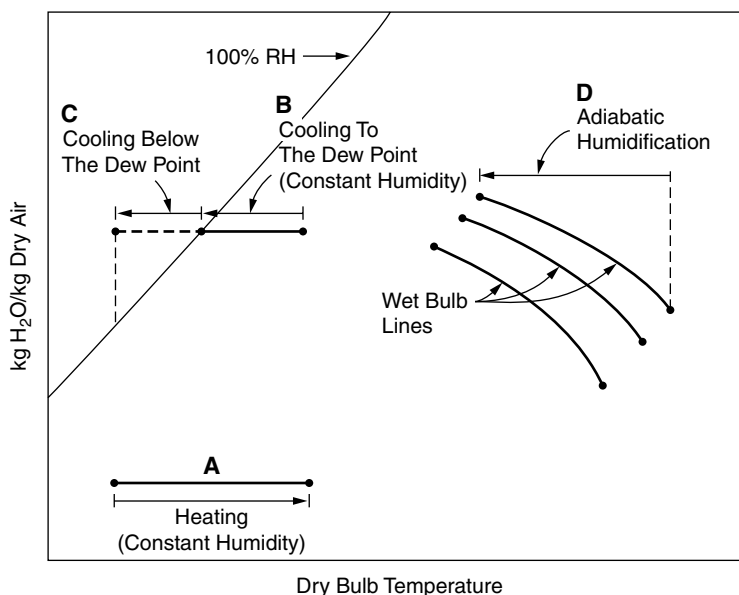


Figure 12.4 Diagram showing paths of cooling, heating, condensation, and adiabatic humidification on a psychrometric chart.

This is the process that occurs when air is passed over or through a bed of wet solids in drying, or when air is passed through water sprays in a water cooling tower.

Example 12.9. Ambient air at 25°C and 50% RH is heated to 175°C. Determine (a) the % RH, and (b) the wet bulb temperature of the heated air.

Solution:

Use the psychrometric chart and draw a vertical line representing $T_{db} = 25^\circ\text{C}$. Project this line until it intersects the diagonal line representing 50% RH. Draw a horizontal line and project to the ordinate to determine the absolute humidity. $H = 0.0098 \text{ kg/water/kg dry air}$. Project the horizontal line representing $H = 0.0098$ until it intersects a vertical line representing $T_{db} = 175^\circ\text{C}$. At the intersection, the % RH can be interpolated between the diagonal lines representing 0.15 % RH and 0.2 % RH. (a) % RH = 0.18 %.

From the intersection, draw a line parallel to the wet bulb line and project to its intersection with the line representing 100% RH. Project the intersection to the abscissa and read (b) $T_{wb} = 45^\circ\text{C}$.

12.4 SIMULTANEOUS HEAT AND MASS TRANSFER IN DEHYDRATION

In dehydration, moisture is removed by evaporation. Heat must be transferred to equal the heat of vaporization. If the rate of mass transfer exceeds heat transfer needed to supply the heat of vaporization, the material will drop in temperature. This process is called evaporative cooling. The mass transfer

equation (Eq. 12.47) can be written for a material undergoing dehydration in the form:

$$\frac{dW_w}{Adt} = k_{gw}(H_i - H) \quad (12.57)$$

dW_w/dt is mass of water transferred, H_i is the humidity at the interface where water is vaporized, and H is the humidity of the drying air. H_i is the equilibrium humidity at the interface at the temperature at the interface. When the temperature at the interface drops, H_i will also drop and the rate of mass transfer will slow down according to Equation (12.57).

Rate of heating needed to vaporize water at the rate dW_w/dt , will be

$$q = \frac{dW_w}{dt} h_{fg}$$

where h_{fg} is the enthalpy of vaporization at the temperature of the interface. Heat transfer needed for vaporization will be

$$q = k_{fg}(A)(H_i - H)(h_{fg}) \quad (12.58)$$

At equilibrium, the heat for vaporizing the mass transferred (Eq. 12.58) will equal the rate of heat transfer (Eq. 12.59). The temperature and humidity at the interface will be T_s and H_s , respectively.

$$q = hA(T - T_s) \quad (12.59)$$

Equating Equations (12.58) and (12.59):

$$(h_{fg})k_{gw}(A)(H_s - H) = hA(T - T_s)$$

$$H = H_s - \frac{hT_s}{k_{gw}(h_{fg})} + \frac{h}{k_{gw}(h_{fg})}T \quad (12.60)$$

Equation (12.60) is the equation of a wet bulb line, the relationship between equilibrium temperature and humidity when a thermometer bulb is wrapped with a wet sock and exposed to a flowing stream of air. The line will go through the point T_s and H_s the wet bulb temperature and the saturation humidity at the wet bulb temperature, respectively.

Food products during drying will follow the relationship between heat and mass transfer as expressed in Equations (12.58), (12.59), and (12.60).

The difference between the dry bulb, T , and the wet bulb temperature, T_s , is known as the wet bulb depression, an index of the drying capacity of a stream of air.

If the temperature of a product during dehydration is higher than the wet bulb temperature, then the rate of heat transfer (Eq. 12.59) exceeds evaporative cooling by mass transfer (Eq. 12.58) and mass transfer controls the drying rate. This phenomenon is often observed in the later stages of drying when the interface for vaporization is removed from the surface requiring vapor to flow through the pores of the dried material close to the surface, before mixing with the drying air at the surface.

The air temperature drops as it undergoes adiabatic humidification. Vaporization of water to increase the humidity requires energy which comes from a drop in the sensible heat of air. The heat balance is as follows.

Heat of vaporization, q_v to increase humidity from H to H_s is

$$q_v = (H_s - H)(h_{fg}) \quad (12.61)$$

The loss in sensible heat q_s for air with a specific heat C_p is

$$q_s = C_p(T - T_s) \quad (12.62)$$

Equating Equations (12.61) and (12.62):

$$C_p(T - T_s) = (H_s - H)(h_{fg}) \quad (12.63)$$

$$H = H_s + \frac{C_p}{h_{fg}} T_s - \frac{C_p}{h_{fg}} T$$

Equation (12.63) is the adiabatic humidification line; the change in humidity of air as it drops in temperature during adiabatic humidification. Equation (12.63) will be exactly equal to Equation (12.60) if the ratio of the heat transfer coefficient to the mass transfer coefficient, h/k_{gw} , equals the specific heat of air, C_p . Indeed, this has been shown to be true for water vaporizing into air at one atmosphere and at moderate temperatures. Thus, in air drying, wet bulb lines on the psychrometric chart coincide exactly with the adiabatic humidification lines.

Example 12.10. Room air at 80°F (26.7°C) and 50% RH is heated to 392°F (200°C) and introduced into a spray drier where it leaves at a temperature of 203°F (95°C).

Determine the humidity and relative humidity of the air leaving the drier. Assume adiabatic humidification in the drier.

Solution:

Using a psychrometric chart, locate the point that represents $T = 80^\circ\text{F}$ and 50% RH. The humidity at this point is 0.011. When air is heated, the temperature increases at constant humidity. Air leaving the heater will have a humidity of 0.011 and a temperature of 392°F (200°C). Starting from $T = 392^\circ\text{F}$ (200°C) and $H = 0.011$, draw a curve that approximates the closest wet bulb curve until a temperature of 203°F (95°C) is reached. The humidity at this point is 0.055 and the relative humidity is 10%.

12.5 THE STAGES OF DRYING

Drying usually occurs in a number of stages, characterized by different dehydration rates in each of the stages. Figure 12.5 shows the desorption isotherm and the rate of drying of apple slices in a cabinet dryer with air flowing across the trays containing the slices at 0.3 m/s, 150°F (65.6°C) and 20% RH. The drying rate curve shows a constant drying rate (line AB) from a starting moisture content of 8.7 g H₂O/g dry matter to a moisture content of 6.00 kg H₂O/kg dry matter. At this stage in the drying cycle, vaporization is occurring at the product surface and free water with a_w of 1.00 is always available at the surface to vaporize. This stage of drying is the constant rate stage. The rate of drying is limited by the rate at which heat is transferred into the material from air. The product temperature is usually at the wet bulb temperature of the drying air.

From a moisture content of 6.00 g H₂O/g dry matter, drying rate decreased linearly with the moisture content. Point B is the critical moisture content and line BC represents the first falling rate period. The first falling rate period is characterized by a slight increase in the temperature of the product, although this temperature may not be very much higher than the wet bulb temperature. Free moisture is no longer available at the surface and the rate of drying is controlled by moisture diffusion towards the surface. Most of the water in the material is still free water with a_w of 1. However, diffusion toward the surface is necessary for vaporization to occur.

From a moisture content of 1.20 g H₂O/g dry matter, the slope of the drying rate against moisture content changes and the rate of drying goes through a second falling rate period. The second falling rate period starts at point C, where the equilibrium relative humidity for the material begins to drop below

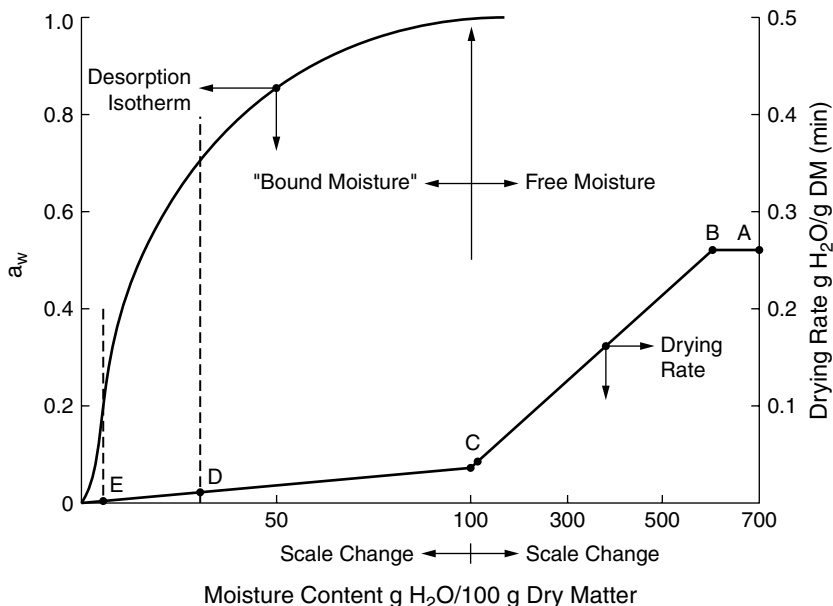


Figure 12.5 Desorption isotherm of raw apple slices and drying rates at different moisture contents.

100%. The moisture content at point C is the bound water capacity of the material. During the second falling rate period, dehydration proceeds through the portion of the sorption isotherm where water in the material is held by multimolecular adsorption and capillary condensation. Heat of vaporization of water in this stage of the dehydration process is higher than the heat of vaporization of pure water because the heats of adsorption and vaporization must be provided. Vaporization at this stage occurs at the interior rather than the surface and water vapor has to diffuse to the surface before it mixes with the flowing stream of air.

At a moisture content of 0.30 g H₂O/g dry matter, the drying rate goes through another falling rate zone. This stage of drying corresponds to the region of the sorption isotherm where water is held in mono- or multi-molecular layers. Dehydration should be terminated at any point along the line DE. Point E represents the equilibrium moisture content where dehydration stops because a_w of the surface and air are equal.

12.6 PREDICTION OF DRYING TIMES FROM DRYING RATE DATA

12.6.1 Materials with One Falling Rate Stage Where the Rate of Drying Curve Goes Through the Origin

The drying rate curve for these materials will show a constant rate R_c from the initial moisture content X_0 to the critical moisture content X_c . The drying rate then falls in a linear relationship with decreasing moisture content until it becomes 0 at $X = 0$. The drying times required to reach a moisture

content X in either of the stages of drying are

$$\text{Constant rate : } -\frac{dX}{dt} = R_c \quad (12.64)$$

The total time, t_c , for the constant rate stage is

$$t_c = \frac{X_0 - X_c}{R_c} \quad (12.65)$$

$$\text{At the falling rate period : } -\frac{dX}{dt} = \frac{R_c}{X_c}(X) \quad (12.66)$$

$$\int_{t_c}^t dt = \frac{X_c}{R_c} \int_{X_c}^X \frac{dX}{X}$$

$$t - t_c = \frac{X_c}{R_c} \ln \frac{X_c}{X} \quad (12.67)$$

The total time from X_0 to X in the falling rate stage can be calculated by substituting t_c in Equation (12.65) into Equation (12.67).

$$t = \frac{X_0 - X_c}{R_c} + \frac{X_c}{R_c} \ln \frac{X_c}{X} \quad (12.68)$$

Equation (12.68) shows that if a material exhibits only one falling rate stage of drying and the drying rate is 0 only at $X = 0$, the drying time required to reach a desired moisture content can be determined from the constant rate R_c , and the critical moisture content X_c . For these materials, X_c is usually the moisture content when a_w starts to drop below 1.0 in a desorption isotherm.

Example 12.11. A material shows a constant drying rate of 0.15 kg H₂O/min (kg dry matter), and has an a_w of 1.0 at moisture contents > 1.10 kg H₂O/kg dry matter. How long will it take to dry this material from an initial moisture content of 75% (wet basis) to a final moisture content of 8% (wet basis)?

Solution:

Converting the final and initial moisture contents from wet to a dry basis:

$$X_0 = \frac{0.75 \text{ kg water}}{0.25 \text{ kg dry matter}} = 3.0 \text{ kg water/kg dry matter}$$

$$X = \frac{0.08 \text{ kg water}}{0.92 \text{ kg dry matter}} = 0.0869 \text{ kg water/kg dry matter}$$

$$X_c = 1.10 \text{ kg water/kg dry matter}$$

$$R_c = 0.15 \text{ kg water/min (kg dry matter)}$$

Using Equation (12.68):

$$t = \frac{3.0 - 1.10}{0.15} + \frac{1.10}{0.15} \ln \frac{1.10}{0.0869} = 12.7 + 18.6 = 31.3 \text{ min}$$

12.6.2 Materials with More Than One Falling Rate Stage

Most food solids would exhibit this drying behavior. The drying rate curve shown in Fig. 12.5 for apple slices is a typical example. The drying time in the constant rate follows Equation (12.65). However, because the rate of drying against moisture content plot no longer goes to the origin from the point (X_c, R_c) , Equation (12.66) cannot be used for the falling rate stage. If the rate versus moisture content line is extended to the abscissa, the moisture content where rate is 0 may be designated as the residual moisture content X_r and for the first falling rate period:

$$\frac{d(X - X_{r1})}{dt} = \frac{R_c}{X_{c1} - X_{r1}}(X - X_{r1}) \quad (12.69)$$

Integrating Equation (12.69) and using Equation (12.65) for drying time in the constant rate zone, drying to a moisture content X in the first falling rate stage would take:

$$t = \frac{X_0 - X_{c1}}{R_c} + \frac{X_{c1} - X_{r1}}{R_c} \ln \frac{X_{c1} - X_{r1}}{X - X_{r1}} \quad (12.70)$$

where X_{c1} and X_{r1} represent the critical moisture content and the moisture content at the end of the first falling rate stage of drying. The time required to dry to moisture content X in the second falling rate stage would be

$$t = \frac{X_0 - X_{c1}}{R_c} + \frac{X_{c1} - X_{r1}}{R_c} \ln \left[\frac{X_{c1} - X_{r1}}{X_{c2} - X_{r1}} \right] + \left[\frac{X_{c1} - X_{r1}}{R_c} \right] \left[\frac{X_{c2} - X_{r2}}{R_c} \right] \ln \left[\frac{X_{c2} - X_{r2}}{X - X_{r2}} \right] \quad (12.71)$$

Example 12.12. Figure 12.6 shows the drying curve for apple slices blanched in 10% sucrose solution and dried in a cabinet drier using air in parallel flow at a velocity of 3.65 m/s at $t_{db} = 170^\circ\text{F}$ (76.7°C) and $T_{wb} = 100^\circ\text{F}$ (37.8°C) for the first 40 minutes, and $T_{db} = 160^\circ\text{F}$ (71.1°C) and $T_{wb} = 110^\circ\text{F}$ (43.3°C) for the rest of the drying period. Calculate the drying time to reach a moisture content of 0.15 kg water/kg dry matter.

Solution:

The drying rate curve was obtained by drawing tangents to the drying curve at the designated moisture contents and determining the slopes of the tangents. The drying time required to obtain a moisture content of 0.15 kg water/kg dry matter will be

$$\begin{aligned} t &= \frac{5.3 - 2.5}{0.163} + \frac{2.5 - 0.35}{0.163} \ln \left[\frac{2.5 - 0.35}{1.0 - 0.35} \right] + \left[\frac{2.5 - 0.35}{0.163} \right] \left[\frac{1 - 0.1}{0.163} \right] \ln \left[\frac{1 - 0.1}{0.15 - 0.35} \right] \\ &= 20.2 + 15.8 + 52.7 = 88.7 \text{ min} \end{aligned}$$

The drying curve in Fig. 12.6 shows a drying time of 90 min at $X = 0.15$.

12.6.3 The Constant Drying Rate

The constant drying rate R_c is heat transfer controlled and can be calculated using a heat balance. Let ρ_s = the dry solids density, kg dry solids/m³ of wet material. ρ_s = wet material density x mass fraction dry solids in the wet material.

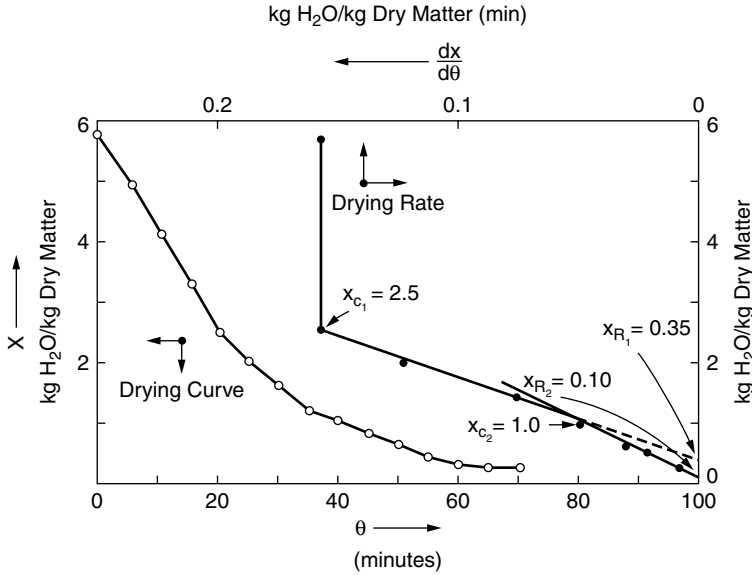


Figure 12.6 Drying curve and drying rate as a function of the moisture content of blanched apple slices, showing several breaks in the drying rate.

If L is the depth of the innermost section of the material from the drying surface (if drying occurs from both sides, L will be half the total thickness of the solid), M_s is the mass of dry solids and A is the area of the top surface of the solid, the volume V of material will be

$$V = \text{surface area (depth)} = A(L) = \frac{M_s}{\rho_s}$$

$$\frac{A}{M_s} = \frac{1}{L(\rho_s)} \quad (12.72)$$

Heat balance: latent heat of evaporation = heat transferred

$$\frac{dX}{dt} M_s h_{fg} = h A (T_a - T_s) \quad (12.73)$$

where h_{fg} = latent heat of vaporization at the surface temperature of the material, T_s , T_a = the dry bulb temperature of the air, and h is the heat transfer coefficient. The surface temperature during the constant rate period is also the wet bulb temperature (T_{wb}) of the air. $T_s = T_{wb}$. $dX/dt = R_c$.

$$R_c = \frac{h(T_a - T_s)}{h_{fg}} \cdot \frac{A}{M_s} \quad (12.74)$$

Substituting Equation (12.72) in Equation (12.74):

$$R_c = \frac{h(T_a - T_s)}{h_{fg} L \rho_s} \quad (12.75)$$

Equation (12.75) can be used to calculate the constant rate of drying from the heat transfer coefficient and the wet and dry bulb temperatures of the drying air for a bed of particles with drying air flowing parallel to the surface.

Expressions similar to Equation (12.75) may be derived using the same procedure as above for cubes with sides L evaporating water at all sides:

$$R_c = \frac{6h(T_a - T_s)}{h_{fg} L \rho_s} \quad (12.75a)$$

For a brick-shaped solid with sides “ a ” and “ $2a$ ” and thickness L :

$$R_c = \frac{h(T_a - T_s)}{h_{fg} \rho_s} \left[\frac{3}{a} + \frac{2}{L} \right] \quad (12.75b)$$

For a spherical solid: $R_c = 3h(T_a - T_s)/(Rh_{fg})$.

The heat transfer coefficient can be calculated using the following correlation equations (Sherwood, Ind. Eng. Chem. 21:976, 1029):

If air flow is parallel to the surface:

$$h = 0.0128G^{0.8} \quad (12.76)$$

where h = the heat transfer coefficient in $\text{BTU}/(\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F})$ and G is the mass rate of flow of air, $\text{lb}_m/(\text{hft}^2)$. In SI units, Equation (12.76) is

$$h = 14.305G^{0.8} \quad (12.77)$$

where $h = \text{W}/(\text{m}^2 \cdot \text{K})$ and G is in $\text{kg}/(\text{m}^2 \cdot \text{s})$. If flow is perpendicular to the surface:

$$h = 0.37G^{0.37} \quad (12.78)$$

where h is in $\text{BTU}/(\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F})$ and G is in $\text{lb}_m/(\text{ft}^2 \cdot \text{h})$. In SI units, Equation (12.78) is

$$h = 413.5G^{0.37} \quad (12.79)$$

where h is in $\text{W}/(\text{m}^2 \cdot \text{K})$ and G is in $\text{kg}/(\text{m}^2 \cdot \text{s})$.

When air flows through the bed of solids, Ranz and Marshall's equation (Chem. Eng. Prog. 48(3):141, 1956; Appendix Table A.12 for particles in a gas stream) may be used for determining the heat transfer coefficient.

Example 12.13. Calculate the constant drying rate for blanched apple slices dried with air flowing parallel to the surface at 3.65 m/s. The initial moisture content was 85.4% (wet basis) and the slices were in a layer 0.5 in. (0.0127 m) thick. The wet blanched apples had a bulk density of approximately 35 lb/ft^3 (560 kg/m^3) at a moisture content of 87% (wet basis).

Dehydration proceeds from the top and bottom surfaces of the tray. Air is at 76.7°C (170°F) db and 37.8°C (100°F) wb.

$$\rho_s = \frac{560 \text{ kg}}{\text{m}^3} \frac{0.13 \text{ kg DM}}{\text{kg}} = 72.8 \frac{\text{kg DM}}{\text{m}^3} \text{ or } 4.55 \frac{\text{lb DM}}{\text{ft}^3}$$

$$V = 3.65 \text{ m/s or } 12.0 \text{ ft/s}$$

Solution:

Using the ideal gas equation: $R = 8315 \text{ Nm/kgmole} \cdot \text{K}$; $T = 76.7^\circ\text{C}$, $P = 1 \text{ atm} = 101.3 \text{ kPa}$, $M = 29 \text{ kg/kg mole}$.

$$\frac{\text{kg air}}{\text{m}^3} = \frac{P(M)}{R(T)} = \frac{(101,300)(29)}{8315(349.7)} = 1.01 \frac{\text{kg}}{\text{m}^3} \text{ or } 0.063 \frac{\text{lb}}{\text{ft}^3}$$

$$G = \frac{\text{kg air}}{\text{m}^3} \times \text{velocity} = 1.01 \frac{\text{kg}}{\text{m}^3} 3.65 \frac{\text{m}}{\text{s}}$$

$$= 3.687 \text{ kg}/(\text{m}^2 \cdot \text{s}) \text{ or } 2713 \text{ lb}/(\text{ft}^2 \cdot \text{h})$$

Using Equation (12.77):

$$h = 14.305(3.687)^{0.8} = 40.6 \text{ W}/(\text{m}^2 \cdot \text{K}) \text{ or } 7.15 \text{ BTU}/(\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F})$$

$$T_a - T_s = 76.7 - 37.8 = 38.9^\circ\text{C} \text{ or } 70^\circ\text{F}$$

$$h_{fg} = \text{heat of vaporization at } 37.8^\circ\text{C} (100^\circ\text{F}) = 1037.1 \text{ BTU/lb or } 2.4123 \text{ MJ/kg}$$

Because drying occurs on top and bottom surfaces, $L = 0.0127/2 = 0.00635$.

Using Equation (12.75):

$$R_c = \frac{40.6(38.9)}{2.4123 \times 10^6(0.00635)(72.8)} = 0.00146 \frac{\text{kg water}}{\text{s} \cdot \text{kg DM}} = 5.098 \text{ kg water}/(\text{h} \cdot \text{kg DM})$$

12.7 SPRAY DRYING

Spray drying is a process where a liquid droplet is rapidly dried as it comes in contact with a stream of hot air. Figure 12.7 is a schematic diagram of a spray drier where the atomized feed travels concurrent with the drying air. The small size of the liquid droplets allows very rapid drying and the residence time of the material inside the spray drier is in the order of seconds. The dried material is separated from air in a cyclone separator. The dried material is continuously withdrawn and cooled. Heat could damage the product if contact with the high temperature drying air is prolonged.

While the droplet is drying, the temperature remains at the wet bulb temperature of the drying air. For this reason, very high temperatures of the drying air can be tolerated in a drier with a minimum of damage to the heat sensitive components. Furthermore, rate of degradative reactions in foods slows down at low moisture contents. Thus, the portion of the drying process where product temperatures goes higher than the wet bulb temperature does not result in severe heat damage to the product.

A major requirement of successful spray drying is the reduction of the moisture content of a liquid droplet to a dryness level that would prevent the particle from sticking to a solid surface, as the particle impinges on that surface. The rate of drying of the particles must be such that from the time the particle leaves the atomizer to the time it impinges upon the walls of the spray drier, the particle is dry. The trajectory and velocity of the particles determines the available drying time. The rate of drying and the time required to dry are dependent upon the temperature of the drying air, the heat transfer coefficient and the diameter of the droplet being dried.

A constant rate and a falling rate drying stage are also manifested in a spray drying process. As the wet droplets leave the atomizer, their surfaces rapidly lose water. Solidified solute and suspended solids rapidly form a solid crust on the surface of each particle. The diameter of the particle usually

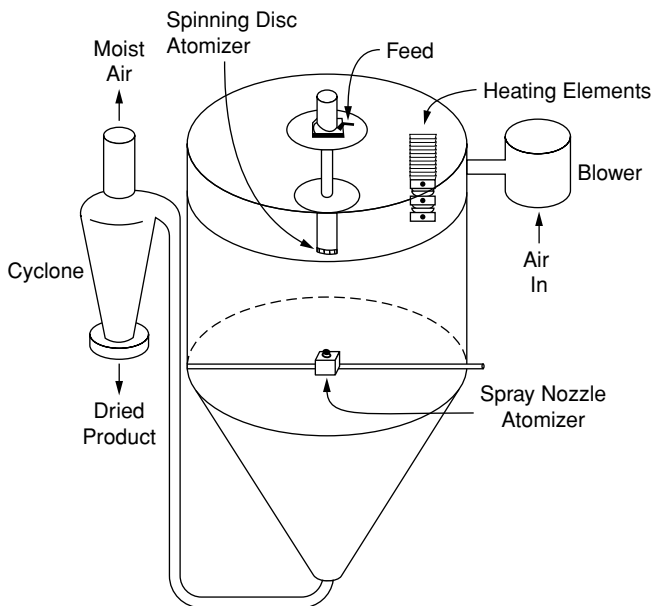


Figure 12.7 Schematic diagram of a spray drier.

decreases as drying proceeds. The formation of the solid crust constitutes the constant rate stage of drying. When the crust becomes sufficiently thick to offer considerable resistance to movement of water toward the surface, the drying rate drops, and the rate of drying is controlled by the rate of mass transfer. The temperature of the particle increases and the liquid trapped in the interior of the particle vaporizes and generates pressure. Eventually, a portion of the crust breaks and the vapor is released. Spray dried particles consist of hollow spheres or fragments of spheres. This shape of the particles is responsible for the excellent rehydration properties of spray dried powders.

12.7.1 Drying Times in Spray Drying

Drying rates in the constant rate period are generally heat transfer controlled and the heat balance is given in Equation (12.73). If ρ_L is the density of the liquid being dried, r is the radius of the droplet, and X_0 is the initial moisture content (dry basis, kg water/kg dry matter);

$$M_s = \frac{4\pi r^3(\rho_L)}{3(1 + X_0)}$$

and Equation (12.73) becomes:

$$\frac{dX}{dt} \cdot \frac{4\pi r^3(\rho_L)(h_{fg})}{3(1 + X_0)} = h(\pi r^2)(T_a - T_s)$$

The constant drying rate in Equation (12.75) can be determined if the heat transfer coefficient h and the radius of the liquid droplets are known. T_s during the constant drying stage would be the wet bulb

temperature of the drying air. Integrating Equation (12.80), the constant rate drying time t_c is

$$\frac{dX}{dt} = \frac{3(1 + X_0)(h)(T_a - T_s)}{4r\rho_L h_{fg}} \quad (12.80)$$

$$t_c = \frac{4(X_0 - X_c)(r)(\rho_L)h_{fg}}{3(1 + X_0)(h)(T_a - T_s)} \quad (12.81)$$

For water vaporizing from a very small spherical particle in slow moving air, the following relationship has been derived for the limiting case of very small Reynolds number in Froessling's boundary layer equations for a blunt-nosed solid of revolution:

$$\frac{hr}{k_f} = 1.0; \quad h = \frac{k_f}{r} \quad (12.82)$$

k_f in Equation (12.82) is the thermal conductivity of the film envelope around the particle. In spray drying, k_f may be assumed to be the thermal conductivity of saturated air at the wet bulb temperature. Substituting Equation (12.82) in Equation (12.81):

$$t_c = \frac{4(X_0 - X_c)(r^2)(\rho_L)h_{fg}}{3k_f(1 + X_0)(T_a - T_s)} \quad (12.83)$$

t_c represents the critical time in spray drying that must be allowed in a particles' trajectory before it impinges on a solid surface in the drier. The drying time in the falling rate period derived by Ranz and Marshal is

$$t_f = \frac{h_{fg}(\rho_L)(r_c^2)(X_c - X)}{3k_f(\Delta\bar{T})} \quad (12.84)$$

where r_c is the radius of the dried particle and $\Delta\bar{T}$ is the mean temperature between the drying air and the surface of the particle during the falling rate period. $\Delta\bar{T}$ may be considered as a log mean between the wet bulb depression and the difference between the exit air and product temperatures. ρ or liquids that contain a high concentration of suspended solids or crystallizable solutes, there is very little change in the droplet diameter during spray drying. Both r and r_c in Equations (12.83) and (12.84), therefore, may be approximated to be the diameter of the liquid droplet leaving the atomizer.

For centrifugal atomizers, the diameter of the droplets as a function of peripheral speed of the atomizer is shown in Fig. 12.8. For pneumatic atomizers, a graph of drop diameter as a function of atomizing air pressure at different liquid flow rates is shown in Fig. 12.9.

Example 12.14. Calculate the drying time for a liquid atomized in a centrifugal atomizer at a feed rate of 15 lb/min (6.8 kg/min) at a peripheral speed of 200 ft/s. Base the drying time for a particle size representing a diameter larger than that of 90% of the total droplets produced. Assume there is no change in droplet diameter with drying. The liquid originally has a density of 61 lb/ft³ (993 kg/m³) and a moisture content of 8% (wet basis) using air at 347°F (175°C) and a humidity of 0.001 H₂O/dry air. The critical moisture content is 2.00 g H₂O/g dry matter. The dried solids have a density of 0.3 g/cm³. Exit air temperature is 220°F (104.4°C). Product exit temperature is 130°F (54.4°C).

Solution:

From Fig. 12.8, the correction factor for a 15 lb/min feed rate is 0.9. At a peripheral speed of 200 ft/s, the diameter corresponding to 90% cumulative distribution is 310 microns. Using the correction

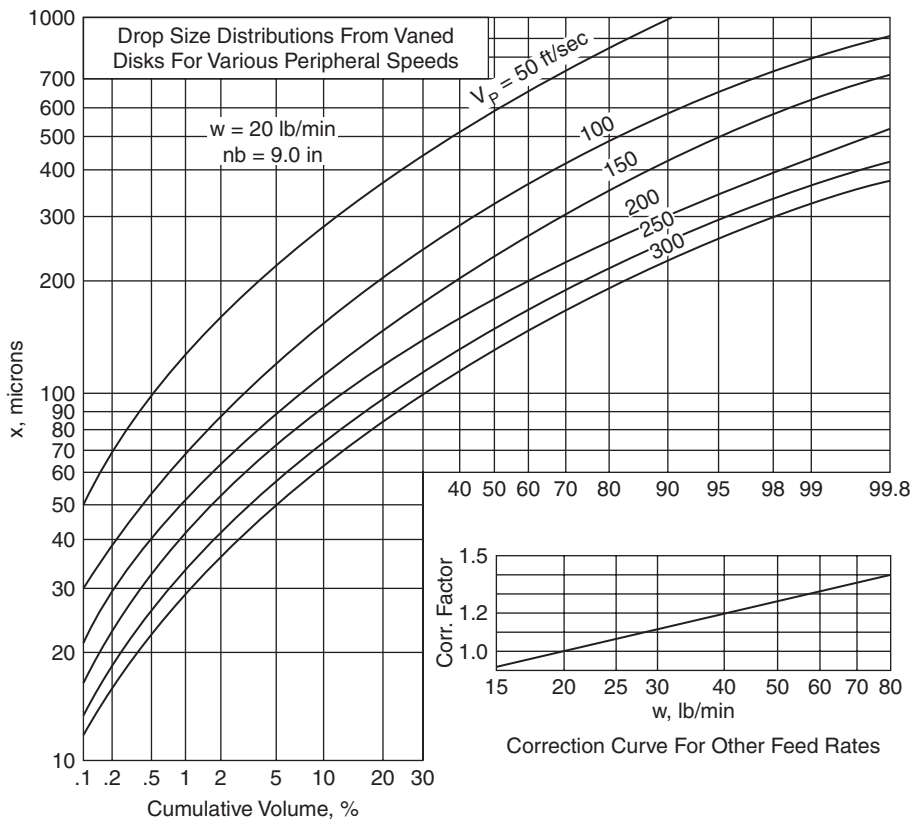


Figure 12.8 Droplet size as a function of peripheral speed of a centrifugal atomizer. (From Marshall, W. R. Jr., 1954. Chem. Eng. Prog. Monogr. Ser. 50(2):71. AIChE, New York. Used with permission.)

factor, the diameter is 279 microns. Using Equations (12.48) and (12.49):

$$X_0 = \frac{89}{11} = 8.09 \text{ kg H}_2\text{O/kg dry matter}$$

$$X_c = 2.00$$

$$X = \frac{0.08}{0.92} = 0.087 \text{ kg H}_2\text{O/kg dry matter}$$

From a psychrometric chart, $T_s = T_{wb} = 109^\circ\text{F}$ (43°C). h_{fg} at 109°F is 1031.4 BTU/lb or 2.3999 MJ/kg. The thermal conductivity of the gas film envelope around the particle can be calculated. It is the thermal conductivity of saturated air at 109°F (43°C). The humidity is 0.056 kg $\text{H}_2\text{O/kg}$ dry matter. The thermal conductivity of dry air is 0.0318 W/m \cdot K and that of water vapor is 0.0235 W/m \cdot K.

$$k_f = 0.318 \frac{1}{1.056} + 0.0235 \frac{0.056}{1.056} = 0.0314 \text{ W/m} \cdot \text{K}$$

$$r = \frac{279}{2} \times 10^{-6} \text{ m} = 139.5 \times 10^{-6} \text{ m}$$

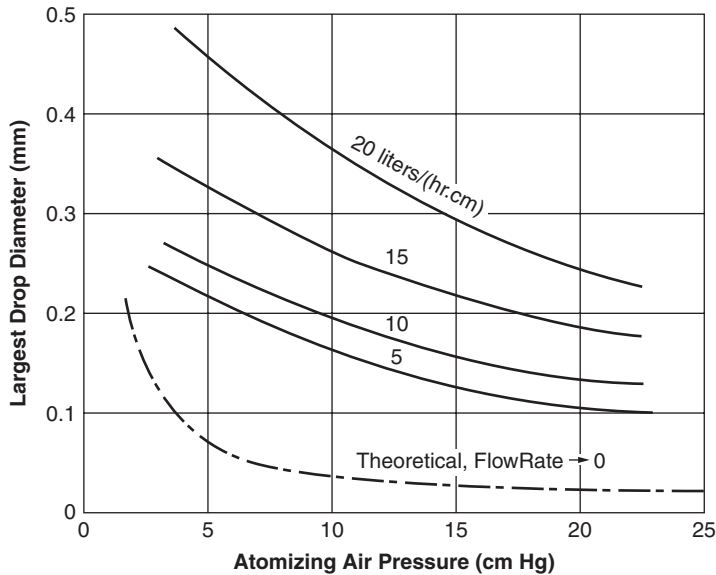


Figure 12.9 Droplet size as a function of pressure in a pneumatic atomizer. (From Marshall, W. R. Jr., 1954. Chem. Eng. Prog. Monogr. Ser. 50(20):79. AIChE, New York. Used with permission.)

Equation (12.81) in SI units:

$$t_c = \frac{4(8.09 - 2)(139.5 \times 10^{-6})^2(993)(2.399 \times 10^6)}{3(0.0314)(1 + 8.09)(175 - 43)} = 10 \text{ s}$$

For Equation (12.84), the $\Delta \bar{T}$ is

$$\Delta \bar{T} = \frac{(175 - 43) - (104.4 - 54.4)}{\ln 132/50} = 84.5 \text{ K}$$

$$t_f = \frac{2.399 \times 10^6(0.3 \times 1000)(193.5 \times 10^{-6})^2(2.0 - 0.087)}{3(0.0314)(84.5)} = 6.5 \text{ s}$$

12.8 FREEZE DRYING

Dehydration carried out at low absolute pressures will allow the vaporization of water from the solid phase. Figure 12.10 shows the vapor pressure of water over ice at various temperatures below the freezing point of water. To carry out freeze drying successfully, the absolute pressure in the drying chamber must be maintained at an absolute pressure of at least 620 Pa.

Figure 12.11 is a schematic diagram of a freeze drier. The absolute pressure inside the drying chamber is determined by the temperature at which the vapor trap is maintained. This pressure corresponds to the vapor pressure over ice at the vapor trap temperature. The vacuum pump is designed primarily to exhaust the vacuum chamber at the start of the operation and to remove noncondensing gases and whatever air leaked into the system. The volume of vaporized water at the low absolute pressures in

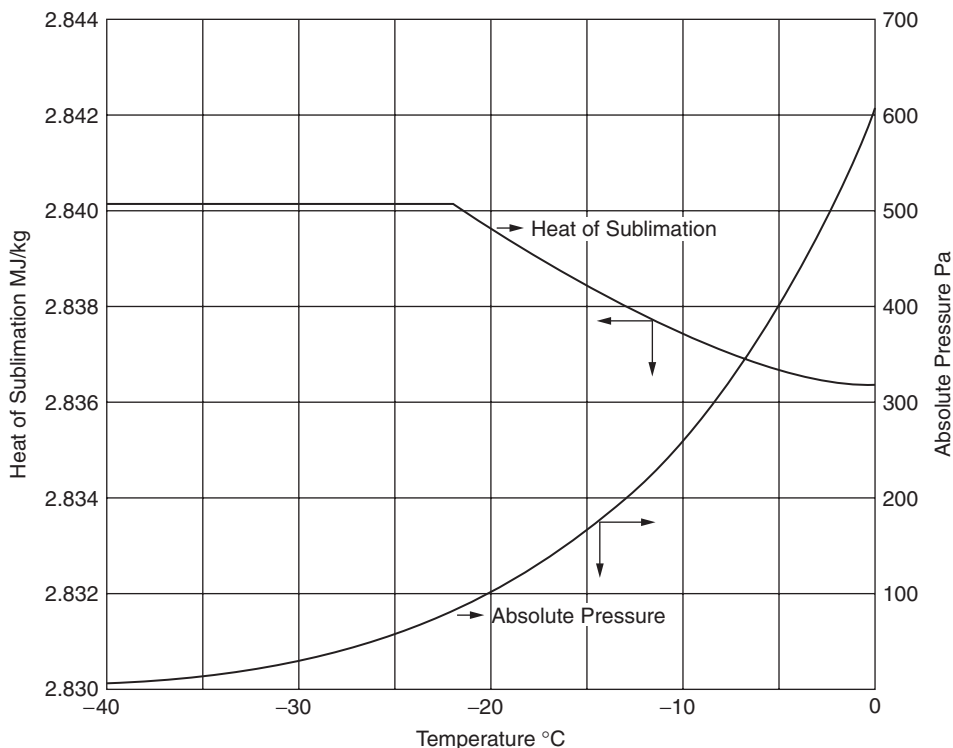


Figure 12.10 Heat of sublimation (ΔH_s) and vapor pressure of water above ice (P_i). (Based on data from Charm, S. E. 1971. Fundamentals of Food Engineering. 2nd ed. AVI Publishing Co. Westport, CT.)

freeze drying is very large; therefore, removal of the vapor by the vacuum pump alone would require a very large pump. Condensing the vaporized water in the form of ice in the vapor trap is an efficient means of reducing the volume of gases to be removed from the system by the vacuum pump.

Heat must also be supplied to the material being dried to provide the energy of vaporization. This is accomplished by the use of hollow shelves through which a heated liquid is circulated. The temperature of the shelves can be regulated by regulating either the temperature or the amount of heat transfer medium supplied to the shelves. The material to be dried rests on the top of the heated shelves. Heat transfer occurs by conduction from the heated shelves, by convection from the air inside the drying chamber to the exposed surfaces and by radiation.

12.8.1 Drying Times for Symmetrical Drying

Analysis of freeze drying is different from that in conventional drying in that drying proceeds from the exposed surfaces toward the interior. The outer layers are completely dry as the ice core recedes. Vaporization of water occurs at the surface of the ice core. Heat of sublimation is conducted to the surface of the ice core through the dried outer layer. Vaporized water diffuses through the pores of the dried outer layer before it leaves the solid and goes to the atmosphere in the drying chamber.

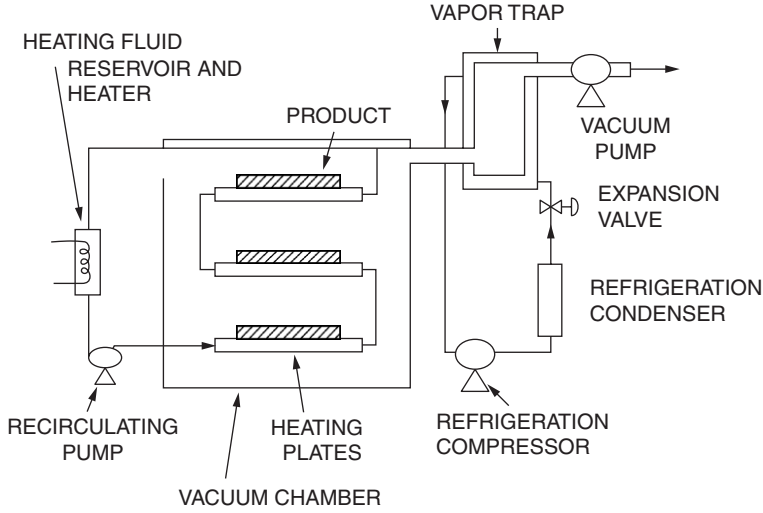


Figure 12.11 Schematic diagram of a freeze drier showing a vapor trap external to the vacuum chamber.

Symmetrical drying occurs when the rate at which the ice core recedes is equal at both top and bottom of the material. To simplify the calculations, unidirectional heat transfer is assumed.

Let $W = \text{kg water/m}^3$ of wet material. If ρ is the density of the wet material and X_0 is the initial moisture content on a dry basis, $\text{kg water/kg dry matter}$, $W = (\rho) X_0 / (1 + X_0)$.

If drying is symmetrical, the mass of water evaporated, M_c , expressed in terms of a dried layer ΔL , is

$$M_c = WA (\Delta L) (2)$$

Let $X' = \text{fraction of water evaporated} = M_c / \text{total water}$.

$$X' = \frac{W(A)(\Delta L)(2)}{W(A)(L)} = \frac{\Delta L(2)}{L}$$

$$X' \text{ is also } \frac{X_0 - X}{X_0}$$

where $L = \text{the thickness of the solid}$. $X = \text{moisture content, kg H}_2\text{O/kg dry matter}$.

$$\Delta L = \frac{L'X}{2}$$

The overall heat transfer coefficient calculated from the sum of the resistance to heat transfer of the dried layer and the heat transfer coefficient at the surface is

$$\frac{1}{U} = \frac{1}{h} + \frac{\Delta L}{k} = \frac{1}{h} + \frac{LX'}{2k} \quad (12.85)$$

$$U = \frac{k}{k/h + LX'/2} \quad (12.86)$$

If drying is symmetrical, heat is transferred from both sides. Let T_s = temperature of the shelf and T_f is the temperature of the frozen core surface. The heat transferred to the ice core will be

$$q = UA\Delta T = \frac{k}{k/h + LX'/2}(2A)(T_a - T_f) \quad (12.87)$$

For simultaneous heat and mass transfer, heat transferred = heat of vaporization. ΔH_s is the heat of sublimation of ice at T_f .

$$\Delta H_s(W)(A)(L)\frac{dX}{dt} = \frac{2A(T_a - T_f)(k)}{k/h + LX'/2} \quad (12.88)$$

Simplifying and integrating Equation (12.88):

$$t = \frac{\Delta H_s(W)(L)}{2k(T_s - T_f)} \left[\frac{k'X}{h} + \frac{LX'^2}{4} \right] \quad (12.89)$$

W in Equation (12.89) can be expressed in terms of either the density of the wet material, ρ , or the density of the dried material ρ_s .

$$W = X_0\rho_s \quad \text{or} \quad W = (\rho)\frac{(X_0)}{1 + X_0}$$

$$t = \frac{\Delta H_s(X_0)(\rho_s)(L)}{2k(T_s - T_f)} \left[\frac{k'X}{h} + \frac{LX'^2}{4} \right] \quad (12.90)$$

Or:

$$t = \frac{\Delta H_s(\rho)(X_0)(L)}{2k(1 + X_0)(T_s - T_f)} \left[\frac{k'X}{h} + \frac{LX'^2}{4} \right] \quad (12.91)$$

Either Equation (12.90) or (12.91) can be used to calculate the time of drying depending on whether ρ or ρ_s is known.

Example 12.15. The density of a sample of beef is 60 lb/ft³ (965 kg/m³). How long will it take to dry a 1 in. (2.54 cm) thick strip of this sample from an initial moisture of 75% to a final moisture content of 4% (wb). Freeze drying is carried out at an absolute pressure of 500 microns of mercury. Assume that the shelf temperature and the air in the drying chamber are equal at 80°F (26.7°C). Assume symmetrical drying. The thermal conductivity of the dried meat is 0.0692 W/m · K. Estimate the heat transfer coefficient by assuming that a 3 mm thick of vapor (k of water = 0.0235 W/m · K) envelopes the surfaces where drying occurs and that the heat transfer coefficient is of equivalent resistance to the resistance of this vapor film.

$$h = \frac{k}{x} = \frac{0.0235}{0.003} = 7.833 \text{ W/m}^2\text{K}$$

The absolute pressure in the chamber is

$$P = 500 \times 10^{-6} \text{ m Hg} \frac{133.3 \times 10^3 \text{ Pa}}{\text{m Hg}} = 66.65 \text{ Pa}$$

From Fig. 12.10, the temperature of ice in equilibrium with a pressure of 66.65 Pa is -24.5°C . The heat of sublimation $H_s = 2.8403 \text{ MJ/kg}$. The final moisture content on a dry basis is $X = 0.04/0.96 = 0.0417 \text{ kg water/kg dry matter}$. The initial moisture content on a dry basis is

$X_0 = -0.75/0.25 = 3.00$. The fraction water remaining at the completion of the drying period is $X' = X_0 - X/X_0 = 3 - 0.0417/3.0 = 0.986$.

Substituting in Equation (12.91):

$$t = \left[\frac{2.8403 \times 10^6 (965)(3.00)(0.0254)}{2(0.0692)(1 + 3)(26.7 + 24.5)} \right] \\ \left[\frac{0.0692(0.986)}{7.833} + \frac{0.0254(0.986)^2}{4} \right] = 109,673 \text{ s} = 30.46 \text{ h}$$

12.9 VACUUM BELT DRYER

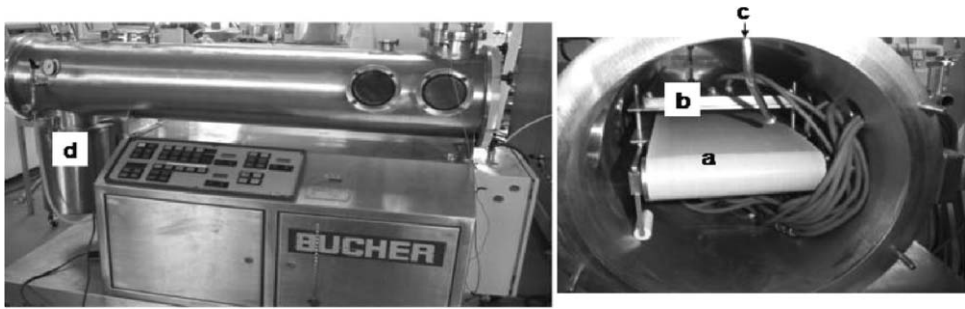
Principle of operation: A vacuum belt dryer is used to dry heat-sensitive pasty materials and concentrated solutions. The system (Fig. 12.12) consists of a long cylinder with a continuous conveyor belt traversing the diameter the whole length of the cylinder. Product is deposited on the belt at one end of the unit and water is evaporated as the belt moves forward until the dried product falls off the belt into a receiver tank at the opposite end.

Energy transfer: Energy to vaporize water is applied to the product on the belt by conduction from the bottom and radiation from the top. A heated plate under the belt heats the product by conduction. Above the conveyor is another heated plate that transfers energy to the paste by radiation. The temperatures of the top and bottom plates are independently controlled and are set to the maximum temperature that would permit complete drying of the product when the belt makes a turn into the opposite direction. Temperatures must be optimized to avoid heat-induced degradation reactions.

Vacuum: Initial evacuation of air from the unit must be done rapidly, and a low absolute pressure must be maintained so that water vapor removal from the product is heat transfer rather than mass transfer controlled. Water vapor and noncondensable gases entering the cylinder must be evacuated using a liquid ring seal mechanical vacuum pump or a steam jet ejector. Typically, an absolute pressure of not more than 50 mm Hg is maintained inside the cylinder. Inadequate vacuum pump capacity will be manifested by condensation of water vapor on the cylinder walls. To facilitate evacuation of water vapor, dry air from the outside is continuously bled into the unit at a slow rate.

Continuous feeding of wet product: The paste to be dried is pumped into the unit and is discharged on the surface of the conveyor belt through a nozzle at the tip of a wand that slowly oscillates from one side of the conveyor belt to the other. Typically, the rate of addition of the paste and the speed of side to side movement of the wand is such that a thin uniform layer of paste is deposited on the belt. As the paste on the belt receives energy from the heated plates, vapor is generated because of the elevated temperature and low absolute pressure. Product on the belt will foam. If the foam forms a thick layer, a porous layer of dried solid forms at the top and bottom hindering heat transfer into the wet middle layer. Ideally, the thickness of the foam should be such that drying will continue throughout the whole thickness all the way to the end of the belt. Spattering of wet material on the belt must also be avoided because the spatter will be deposited on the surface of the plate above the belt and interfere with radiant heat transfer. The combination, vacuum, upper and lower heated plate temperature, and thickness of the deposited layer of wet product on the belt must be carefully regulated to dry successfully in this system.

Operating the drier: Drying time can be controlled by slowing down the speed of the belt. However, to operate at maximum drying capacity, heated plate temperatures must be elevated and too long a residence time of the wet product in the heated zone could result in scorching of the product. Conditions



a- belt; b – top heater plate; c – swivel liquid feed port; d – dried product receiver

Figure 12.12 Picture of a pilot plant size vacuum belt dryer.

must be optimized for each product dried. The paste density, foaming tendency, thermophysical properties and radiant energy absorption all play a role in the rate of dehydration.

PROBLEMS

- 12.1. Pork has a_w of 1.00 at a moisture content of 50% (wet basis) and higher. If pork is infused with sucrose and NaCl and dehydrated such that at the end of the dehydration process the moisture content is 60% (wet basis) and the concentration of sugar and NaCl are 10% and 3%, respectively, calculate the a_w of the cured product.
- 12.2. What concentration of NaCl in water would give the same water activity as a 20% solution of sucrose?
- 12.3. The following data were obtained on the dehydration of a food product: initial moisture content = 89.7% (wet basis).

<i>Drying time (min)</i>	<i>Net weight (kg)</i>
0	24.0
10	17.4
20	12.9
30	9.7
40	7.8
50	6.2
60	5.2
70	4.5
80	3.9
90	3.5

Draw the drying curve for this material and construct a curve for the drying rate as a function of the moisture content.

- (a) What is the critical moisture content for each of the falling rate zones?
 - (b) What is the constant drying rate?
 - (c) Determine the residual moisture content for each of the falling rate stages.
 - (d) The dehydration was conducted at an air flow rate of 50 m/s at a dry bulb temperature of 82°C and a wet bulb temperature of 43°C. The wet material has a density of 947 kg/m³ and were dried in a layer 2.5 cm thick. If the same conditions were used but the initial moisture content was 91% (wet basis) and a thicker layer of material (3.5 cm) were used on the drying trays, how long will it take to dry this material to a final moisture content of 12% (wb)?
- 12.4. A continuous countercurrent drier is to be designed to dry 500 kg/h of food product from 60% (wet basis) moisture to 10% (wet basis) moisture. The equilibrium moisture content for the material is 5% (wet basis) and the critical moisture content is 30% (wet basis). The drying curve of the material in preliminary drying studies showed only one falling rate zone. Air at 66°C dry bulb and 30°C wet bulb will be used for drying. The exit air relative humidity is 40%. Assume adiabatic humidification of the air. The drying air is drawn from room temperature at 18°C and 50% RH. The wet material has a density of 920 kg/m³. The drying tunnel should use trucks that hold a stack of 14 trays, each 122 cm wide, 76 cm deep along the length of the tunnel, and 5 cm thick. The distance between trays on the stack is 10 cm. The drying tunnel has a cross-sectional area of 2.93 m². The material in the trays will be loaded at a depth of 12.7 mm. Calculate:
- (a) The number of trays of product through the tunnel/h.
 - (b) The rate of travel by the trucks through the tunnel. Assume distance between trucks is 30 cm.
 - (c) The constant drying rate and the total time for drying.
 - (d) The length of the tunnel.
 - (e) If air recycling is used, the fraction of the inlet air to the drier that must come from recycled air.
 - (f) The capacity of the heater required for the operation with recycling.
- 12.5. A laboratory drier is operated with a wet bulb temperature of 115°F and a dry bulb temperature of 160°F. The air leaving the drier is at 145°F dry bulb. Assume adiabatic operation. Part of the discharge air is recycled. Ambient air at 70°F and 60% RH is heated and mixed with the recycled hot air. Calculate the proportion of fresh air and recycled hot air that must be mixed to achieve the desired inlet dry and wet bulb temperatures.
- 12.6. If it takes 8 hours to dry a material in a freeze drier from 80% H₂O to 10% H₂O (wet basis) at an absolute pressure of 100 Φ m and a temperature of 110°F (43.3°C), how long will it take to dry this material from 80% to 40% water if the dehydration is carried out at 500 Φ m and 80°F (26.7°C). The material is 25 mm thick, has a density of 950 kg/m³, and the thermal conductivity of the dried material is 0.35 W/m · K. Thermal conductivity and heat transfer coefficients are independent of plate temperature and vacuum.
- 12.7. Calculate the constant rate of drying in a countercurrent continuous belt dehydrator that processes 200 lb/h (90.8 kg/h) of wet material containing 80% water to 30% water. Air at 80° EF (26.7°C) and 80% RH is heated to 180°F (82.2°C) in an electric heater, enters the drier and leaves at 10% RH. The critical moisture content of the material is 28%. The drier is 4 ft (1.21 m) wide, the belt loaded to a depth of 2 in. (5.08 cm) of material, and the clearance from the

top of the drier to the top of the material on the belt is 10 in. (25.4 cm). The density of the dry solids in the material is 12 lb/ft³ (193 kg/m³).

- 12.8. In a spray drying experiment, a sample containing 2.15% solids and 97.8% water was fed at the rate of 6.9 lb per hour (3.126 kg/h) and this sample was dried at 392°F (200°C) inlet air temperature. The exit air temperature was 200°F (93.3°C). The dried product was 94.5% solids and the outside air was at 79°F (26.1°C) and 20% RH.

Calculate:

- (a) The weight water evaporated per hour.
 - (b) The % RH of the exit air.
 - (c) The mass flow rate of air through the drier in weight dry air/h.
 - (d) In this same drier, if the inlet air temperature is changed to 440°F (226.7°C) and the % RH of the exit air were kept the same as in (b), weight of a sample containing 5% solids and 98% water can be dried to 2% water in 1 hour? (Air flow rate is the same as before.) What would be the exit temperature of the air from the drier under the conditions? Assume adiabatic drying.
- 12.9. A dehydrator when operated in the winter where the outside air was 10°F (−12.2°C) and 100% RH ($H = 0.001$) can dry 100 lb (45.5 kg) of fruit per hour from 90% water to 10% water. The inlet temperature of the air to the drier is 150°F (65.6°C) and leaves at 100°F (37.8°C). In the summer when the outside air is at 90°F (32.2°C) and 80% RH, determine the moisture content of the product leaving the drier if the operator maintains the same rate of 100 lb (45.4 kg) of wet fruit/hr and the exit air from the drier has the same % RH as it was in the winter.
- 12.10. The desorption isotherm of water in carrots at 70° EC is reported to fit Iglesias and Chirife's equation (Eq. 12.36) with the constants $B_1 = 3.2841$ and $B_2 = 1.3923$.
- (a) Determine the moisture contents where a shift in drying rate may be expected in the dehydration of carrots.
 - (b) The following data represents the equilibrium water activity (a_w) for carrots at various moisture contents in kg water/kg dry matter (X): (a_w , X); (0.02, 0.0045), (0.04, 0.009), (0.06, 0.0125), (0.08, 0.016), (0.10, 0.019), (0.12, 0.0225), (0.14, 0.025), (0.16, 0.028), (0.18, 0.031), (0.20, 0.034). Fit this data to the BET isotherm and determine the moisture content for a unimolecular layer, X_m
 - (c) Fit the data to the GAB equation and determine the constants.
- 12.11 The diffusivity of water in scalded potatoes at 69° EC and 80% moisture (wet basis) has been determined to be 0.22×10^{-5} m²/h. If 1 cm potato cubes are dried using air at 1.5 m/s velocity and 1% relative humidity, calculate the dry bulb temperature of the air that can be used such that the diffusion rate from the interior to the surface will be equal to the surface dehydration rate. Assume the air flows parallel to the cubes and that dehydration proceeds from all faces of each cube. The density of the potato cube is 1002 kg/m³ at 80% moisture.
- 12.12 Puffing can be induced during dehydration of diced carrots if the dehydration rate at the constant rate period is of the order 1 kg water/(min kg DM). In a fluidized bed drier where the air contacts individual particles at a velocity of 12 m/s, calculate the minimum dry bulb temperature of the drying air that would induce this rate of drying at the constant rate period. Assume drying air has a humidity of 0.001 kg water/kg dry air and surface temperature under these conditions is 5° EC higher than the wet bulb temperature. Calculate the mass transfer rate under these conditions. Is dehydration rate heat or mass transfer controlled?

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