

Drying and Dehydration

10

Abstract. This chapter reviews basic concepts of drying and dehydration, including mass balance analyses. Equilibrium moisture content, water activity, and related parameters are discussed. Drying methods and drier types are briefly discussed.

Keywords. Dehydration, driers, drying, equilibrium moisture content, evaporation, water activity.

10.1 Introduction

Removing water from food and agricultural products constitutes a significant portion of the processing activity for persons working in the food and agricultural processing industries. Two major moisture removal methods are **drying** (or dehydration) to produce a solid product and **evaporation** to produce a more concentrated liquid. The words drying and dehydration are often used interchangeably, especially when referring to food products; however, only the word drying is commonly used when referring to processing of non-food products. Applications range from on-farm drying of grain, fruits, and vegetables to large scale commercial drying of fruits, vegetables, snack food products, milk products, coffee, and other products. Although certain basic factors are involved in all drying processes, the equipment and techniques vary greatly depending upon the product and other factors. In this unit, we will consider some basic factors affecting drying and briefly examine some drying methods.

Evaporation is the removal of some water from a liquid product to produce a more concentrated liquid. Applications include concentration of milk, fruit juices, and syrup products. Most evaporation systems are large-scale commercial operations, although small-scale farm operations still exist for production of maple, sorghum, and sugar cane syrups. The governing principles of evaporator operation will be briefly examined in this unit.

10.2 Moisture Content

No agricultural product in its natural state is completely dry. Some water is always present. This moisture is usually indicated as a percent moisture content for the product. Two methods are used to express this moisture content. These methods are wet basis (m) and dry basis (M). In addition, the content may be expressed as a percent or as a decimal ratio. We will use all four forms (wet basis, dry basis, percent, and decimal ratio) in analyzing moisture or food products.

The general governing equations for indicating moisture content are:

$$m = \frac{m_w}{m_w + m_d} = \frac{m_w}{m_t} \quad (10.01)$$

$$M = \frac{m_w}{m_d} \quad (10.02)$$

where: m = decimal moisture content wet basis (wb)

M = decimal moisture content dry basis (db)

m_d = mass of dry matter in the product

m_w = mass of water in the product

m_t = total mass of the product, water plus dry matter

The percent moisture content is found by multiplying the decimal moisture content by 100.

In addition, relationships between wet and dry moisture content on a decimal basis can be derived from Equations 10.01 and 10.02. Those relationships are:

$$M = \frac{m}{1 - m} \quad \text{or} \quad m = \frac{M}{1 + M} \quad (10.03)$$

Use of the wet basis measurement is common in the grain industry where moisture content is typically expressed as percent wet basis. However, use of the wet basis has one clear disadvantage—the total mass changes as moisture is removed. Since the total mass is the reference base for the moisture content, the reference condition is changing as the moisture content changes. On the other hand, the amount of dry matter does not change. Thus, the reference condition for dry basis measurements does not change as moisture is removed.

For a given product, the moisture content dry basis is always higher than the wet basis moisture content. This is obvious from a comparison of Equations 10.01 and 10.02. The difference between the two bases is small at low moisture levels, but it increases rapidly at higher moisture levels.

A final note regarding moisture content relates to high moisture materials such as fruits and vegetables. Many of these products have moisture contents near 0.90 (or 90%) (wb). On a dry basis this would be 900% if expressed as a percentage. For products of this type, moisture is often given as “mass of water per unit mass of dry product,” the decimal basis we discussed earlier.

Example 10.1

A bin holds 2000 kg of wet grain containing 500 kg of water. This grain is to be dried to a final moisture content of 14% (wb).

- What are the initial and final moisture contents of the grain (wet basis, dry basis, decimal and percent)?
- How much water is removed during drying?

Solution:

Using Equations 10.01 and 10.02 the initial moisture content is:

$$m = \frac{m_w}{m_t} = \frac{500}{2000} = 0.25 \text{ or } \underline{25\% \text{ wet basis (wb)}} \quad \text{ANSWER}$$

$$M = \frac{m_w}{m_d} = \frac{500}{2000 - 500} = 0.3333 \text{ or } \underline{33.33\% \text{ dry basis (db)}} \quad \text{ANSWER}$$

The final moisture content was stated as 14% (wb), or $m = 0.14$. Using Equation 10.03, we can solve for the moisture content on a dry basis:

$$M = \frac{0.14}{1 - 0.14} = \frac{0.14}{0.86} = 0.1628 \text{ or } \underline{16.28\% \text{ (db)}} \quad \text{ANSWER}$$

The amount of water in the dried grain may be found using either Equation 10.01 or 10.02 and the appropriate final moisture content noted above. For our example, we will use both methods. We will first use the dry basis moisture of $M = 0.1628$. Noting that the bin contains 1500 kg of dry matter (2000 – 500), Equation 10.02 gives:

$$m_w = m_d \times M = 1500 \times 0.1628 = 244 \text{ kg}$$

Alternatively, using Equation 10.01 and $m = 0.14$, we find the same solution:

$$m_w = m \times (m_w + m_d) = 0.14 \times (m_w + 1500) = 0.14m_w + 210$$

$$0.86m_w = 210 \Rightarrow m_w = 244 \text{ kg}$$

Thus, the water removed is: $m_{w \text{ rem}} = 500 - 244 = \underline{256 \text{ kg}}$ ANSWER

Many different techniques are available for measuring the moisture content of a material. The technique used in a given instance depends upon the material being studied, equipment available, and the time available for the measurement. The most straightforward method of moisture measurement is to use a drying oven. A sample of the product is heated at a specified temperature and pressure (usually atmospheric pressure or a specified vacuum) for a specified time to remove all moisture (i.e., dry until there is no further weight loss). The loss in mass of the sample represents the moisture removed from the product. The temperature, drying time, and pressure are dependent upon the product being analyzed. Microwave drying ovens and chemical analysis are also used for some moisture measurement applications. An extensive list of standards for moisture measurement is provided by AOAC (1990).

10.3 Equilibrium Moisture Content

A material held for a long time at a fixed temperature and relative humidity will eventually reach a moisture content that is in equilibrium with the surrounding air. This does not mean that the material and the air have the same moisture content. It simply means that an equilibrium condition exists such that there is *no net exchange* of moisture between the material and the air. This **equilibrium moisture content** (*EMC* or M_e) is a function of the temperature, the relative humidity, and the product. These equilibrium moisture relationships are normally expressed mathematically. Numerous

equations have been proposed to represent the EMC curves for various products (Iglesias and Chirfe, 1982; ASAE, 2000). No single equation is suitable for all products; however, most products can be represented by one of several equations available. Four of these equations are listed below. Halsey's equation (Equation 10.04) and Henderson's equation (Equation 10.05) are two of the less complicated equations. Temperature is not a parameter in Halsey's equation. Thus, different constants must be used for each product and temperature of interest. Note also that the constants are valid only for the equation listed and should not be adapted for other equations. Grains and related products are often represented by the slightly more complicated Modified Henderson Equation (Equation 10.06), the Modified Halsey Equation (Equation 10.07), the Modified Oswin Equation, or the Guggenheim-Anderson-DeBoer (GAB) equation (ASAE, 2000). The relative humidity defined by these equations is commonly called the **equilibrium relative humidity** (*ERH*). Thus, *ERH* is the relative humidity for equilibrium between air and a specific product at a given temperature.

$$ERH = \exp\left(\frac{-K}{M_e^N}\right) \quad \text{Halsey} \quad (10.04)$$

$$ERH = 1 - \exp(-K t M_e^N) \quad \text{Henderson} \quad (10.05)$$

$$ERH = 1 - \exp(-K(t + C)M_e^N) \quad \text{Modified Henderson} \quad (10.06)$$

$$ERH = \exp\left(\frac{\exp(K + C t)}{M_e^N}\right) \quad \text{Modified Halsey} \quad (10.07)$$

where: *ERH* = relative humidity, decimal
M_e = equilibrium moisture content, percent, dry basis
t = temperature, °C
K, N, C = are constants determined for each material
 (see Tables 10.01 and 10.02)

A typical set of equilibrium moisture curves are presented in Figure 10.01. These curves are computed using Equation 10.06 and the constants from Table 10.01 for shelled corn. Note that curves begin at 20% relative humidity and are terminated before reaching 100% relative humidity. Prediction curves are generally written to describe conditions in the middle ranges of relative humidity. They do not predict well for extreme conditions. In addition, reliable experimental data are difficult to obtain in those regions.

**Table 10.01. Constants for Modified Henderson and Halsey Equations.
(From ASAE, 2000.)**

Grain	K	N	C	Equation
Beans, pinto	4.4181	1.7571	-0.011875	10.07
Beans, white	0.1633	1.567	87.46	10.06
Canola meal	0.000103	1.6129	89.99	10.06
Corn, shelled	6.6612×10^{-5}	1.9677	42.143	10.06
Popcorn	1.5593×10^{-4}	1.5978	60.754	10.06
Peanut, kernel	3.9916	2.2375	-0.017856	10.07
Pumpkin seed, adsorption*	3.3725×10^{-5}	3.4174	1728.729	10.06
Pumpkin seed, desorption*	3.3045×10^{-5}	3.3645	1697.76	10.06
Rice, med grain	3.5502×10^{-5}	2.31	27.396	10.06
Soybean	2.87	1.38	-0.0054	10.07
Wheat, hard red	4.3295×10^{-5}	2.1119	41.565	10.06

*kernels

Table 10.02. Selected EMC relationships for food products. Constants are valid only for the equation number listed. (From Iglesias and Chirfe, 1982.)

Product	Temperature	rh range	Equation	K	N
Apple	30°C	0.10 - 0.75	10.05	0.1091	0.7535
Apple ^[a]	19.5°C	0.10 - 0.70	10.04	4.4751	0.7131
Banana	25°C	0.10 - 0.80	10.05	0.1268	0.7032
Chives	25°C	0.10 - 0.80	10.04	11.8931	1.1146
Grapefruit	45°C	0.10 - 0.80	10.05	0.1519	0.6645
Mushrooms	20°C	0.07 - 0.75	10.04	7.5335	1.1639
Mushrooms ^[a]	25°C	0.10 - 0.80	10.04	11.5342	1.1606
Peach	20 - 30°C	0.10 - 0.80	10.05	0.0471	1.0096
Peach	40°C	0.10 - 0.80	10.05	0.0440	1.1909
Peach	50°C	0.10 - 0.80	10.05	0.0477	1.3371
Pear	25°C	0.10 - 0.80	10.05	0.0882	0.7654
Tomato	17°C	0.10 - 0.80	10.04	10.587	0.9704

^[a]Desorption isotherm data. All other data is for sorption (moisture addition) measurements.

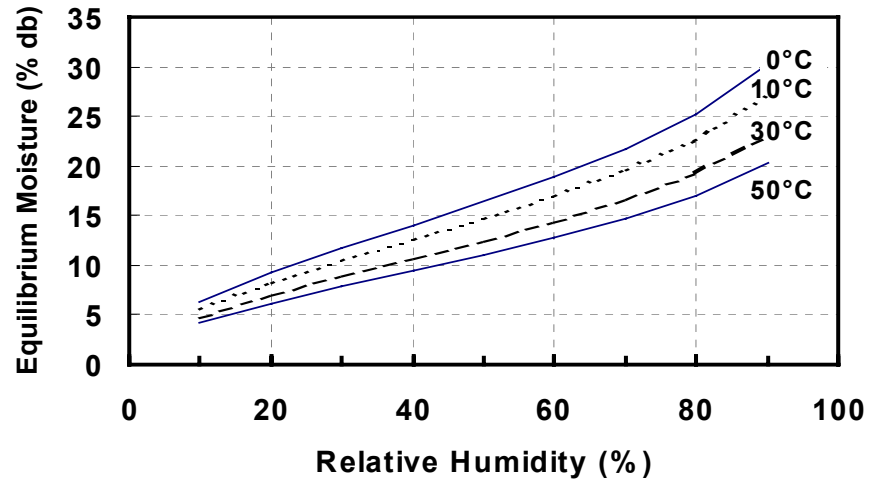


Figure 10.01. Equilibrium moisture curves for shelled corn. Computed from ASAE data (ASAE, 2000).

Example 10.2

Compute the equilibrium moisture content for popcorn at 20°C and 50% relative humidity.

Solution:

We first rearrange Equation 10.06 to express equilibrium moisture in terms of the other parameters:

$$M_e = \sqrt[N]{\frac{\ln(1-ERH)}{-K(t+C)}} = \left(\frac{\ln(1-ERH)}{-K(t+C)} \right)^{\frac{1}{N}}$$

We now substitute values of K, N, and C from Table 10.01 into the equation and solve for M_e at 20°C and 50% relative humidity:

$$M_e = \left(\frac{\ln(1-0.5)}{-1.5593 \times 10^{-4}(20 + 60.754)} \right)^{\frac{1}{1.5978}} = \left(\frac{\ln(0.5)}{-0.01259} \right)^{0.62586}$$

$$= \left(\frac{-0.6931}{-0.01259} \right)^{0.6258} = (55.047)^{0.62586} = \underline{12.19\% \text{ (db)}} \quad \text{ANSWER}$$

10.4 Water Activity (a_w)

The amount of water in food and agricultural products affects the quality and perishability of these products. However, perishability is not directly related to moisture content. In fact, perishability varies greatly among products with the same moisture content. A much better indicator of perishability is the availability of water in the product to support degradation activities such as microbial action. The term **water activity** is widely used in the food industry as an indicator of water available in a product. See Labuza (1984) or Troller and Christian (1978) for further information. Water activity (a_w) is defined as:

$$a_w = \frac{P_w}{P_{ws}} \quad \text{or} \quad a_w = \phi \quad \text{since} \quad \phi = \frac{P_w}{P_{ws}}$$

where: ϕ = the relative humidity, decimal

P_w = the partial pressure of water vapor at the specified conditions

P_{ws} = the partial pressure of water vapor at saturation and the temperature specified

Thus, water activity is the equilibrium relative humidity (*ERH*) in decimal form for a product at a given temperature and moisture content. Figure 10.01 can then be considered as a plot of equilibrium moisture content as a function of a_w , if we change the x-axis scale to decimal form. A more common method for representing the effect of a_w is shown in Figure 10.02. The shape of this graph is typical of water activity graphs although the moisture content scale may vary greatly among products. The key feature of this relationship is that actual moisture content increases rapidly with a_w at the higher values of water activity.

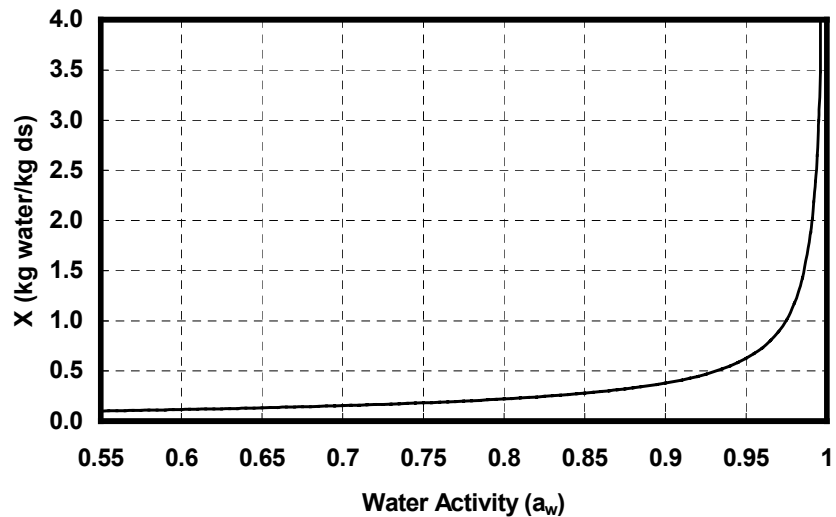


Figure 10.02. Water activity curve for fresh, diced sweet potato cubes.

The physical significance of a_w may not be immediately clear from the above equation. Thus, we will examine a conceptually simple method of determining a_w . If we take a sample of a food product and place it in an enclosed container at a fixed temperature, the product will exchange moisture with the air surrounding it. After a period of time, as with the equilibrium moisture example noted in the previous section, an equilibrium condition will occur. The product no longer has any net change in moisture. The water activity is equal to the decimal relative humidity at that condition.

10.5 Controlling Factors for Drying

Two separate phenomena are involved in drying. First, moisture must move from the interior of a material to the surface of that material. Second, the surface water must be evaporated into the air. These two steps involve two very different phenomena. Movement of water from the interior to the surface must occur in one of two manners—capillary action or diffusion. Movement by capillary action would only occur during early stages of drying. As the drying process continues, internal moisture movement would occur by molecular diffusion of water vapor within the material. Removal of water from the surface involves evaporation of water from the surface into the surrounding air. The evaporation rate depends upon the condition of drying air and the concentration of water at the surface.

Air drying involves the passing of air over the object(s) to be dried. Typically, the air is heated prior to entering the drying region. Consider the drying process for a high moisture product such as an apple slice. The surface of the slice will be visibly covered with water immediately after slicing. As this water evaporates, the surface becomes slightly dry. Moisture cannot move from the interior of the slice as rapidly as it can evaporate at the surface. Thus the governing factor in later stages of drying is the diffusion rate of moisture within the slice.

Factors affecting the drying rate will vary slightly depending upon the type of drying system used. However, in general, the following factors must be considered:

1. nature of the material: physical and chemical composition, moisture content, etc.;
2. size, shape, and arrangement of the pieces to be dried;
3. wet-bulb depression ($t - t_{wb}$), or relative humidity, or partial pressure of water vapor in the air (all are related and indicate the amount of moisture already in the air);
4. air temperature; and
5. air velocity (drying rate is approximately proportional to $u^{0.8}$).

Another factor that must be considered in drying solid materials is case hardening. This problem can occur if the initial stage of drying occurs at low relative humidity and high temperature. Under these conditions, moisture is removed from the surface of the material much faster than it can diffuse from within the material. The result is formation of a hardened relatively impervious layer on the surface of the material. Formation of such a layer causes subsequent drying to be much slower than it would otherwise be.

10.6 Air Drying Methods

Many different drying systems have been developed to meet the needs for drying different materials. A few of the more common systems are described in the following sections.

10.6.1 Bin Drying

Bin drying systems are common in on-farm grain drying operations. The bin is filled with grain and drying air is forced up through the grain from a plenum chamber beneath the perforated floor of the bin. The grain on the bottom is dried first. As drying progresses a layer of drying grain separates the dried grain from the undried grain. This region of drying grain is called a drying front. This drying front progresses upward through the bin of grain until all grain is dried. Figure 10.03 shows a representation of this process. Other on-farm drying methods include stirring of grain in the bin during drying and use of continuous flow dryers to dry grain before storage. The arrangement shown in Figure 10.03 is very useful for studying drying systems since it can be readily analyzed for mass and energy balances.

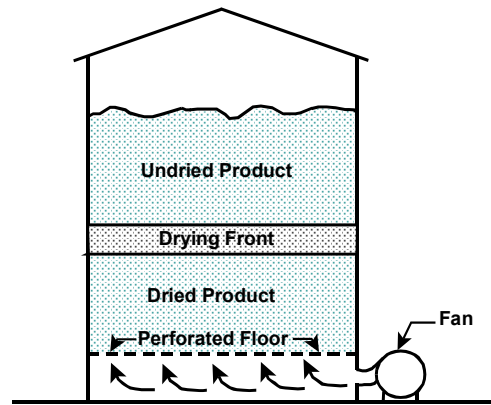


Figure 10.03. Bin drying diagram showing the drying front with about half the product dried.

10.6.2 Cabinet Drying

Cabinet dryers are usually small, insulated units with a heater, circulating fan, and shelves to hold the product to be dried. The small dehydration units sold for home use are small-scale examples of this type of dryer. Different designs are used, but the general procedure is to force heated air over multiple trays. Small-scale cabinet dryers are typically single pass units. However, greater energy efficiencies can be obtained if some of the heated air is recirculated. This is especially true in later stages of drying when the moisture removal rate is low and the exit air retains considerable moisture-holding capacity. Figure 10.04 shows the basic operation of a cabinet dryer with recirculation. Energy savings of 50% or more can be achieved with recirculation.

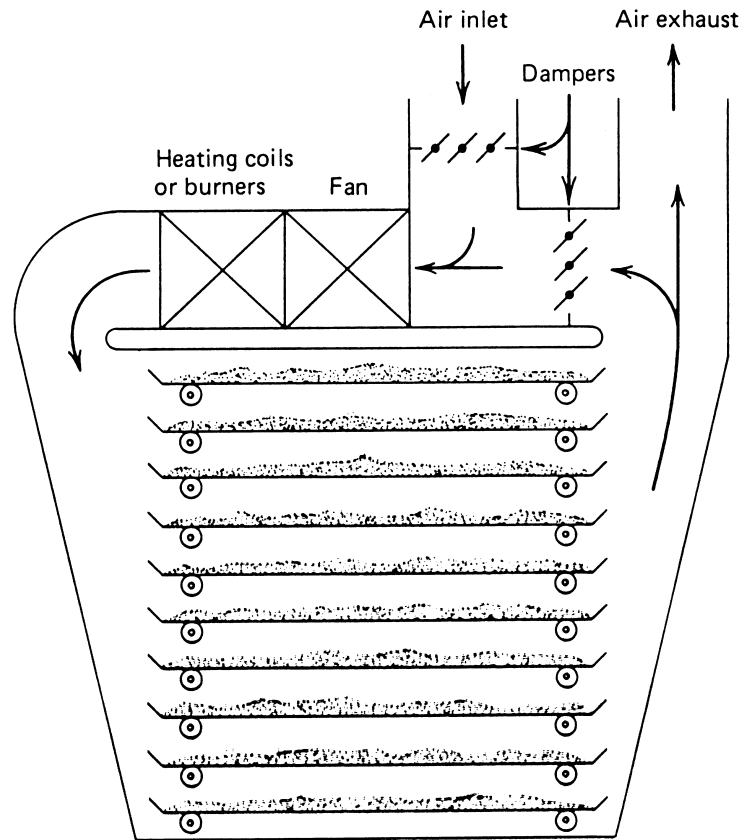


Figure 10.04. Sketch of a cabinet dryer with recirculation.

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10.6.3 Tunnel Drying

Tunnel dryers are a large-scale modification of the cabinet dryer concept. The drying chamber is a tunnel with multiple carts containing trays of the product being dried. New carts of undried product are loaded at one end of the tunnel as carts of dried product are removed from the other end. Air flow in these dryers may be parallel or counter to the movement of carts in the tunnel. Figure 10.05 shows examples of parallel and counter flow tunnel dryers.

10.6.4 Drum Drying

Large rotating drums are used for drying slurries (liquids with a high solids content). A thin film of the slurry is deposited on the bottom of a rotating drum as it passes through the slurry. The slowly rotating drum is heated and sometimes held under a vacuum. The dried product is scraped from the drum before the rotating surface re-enters the slurry. Figure 10.06 shows four different configurations of drum dryers.

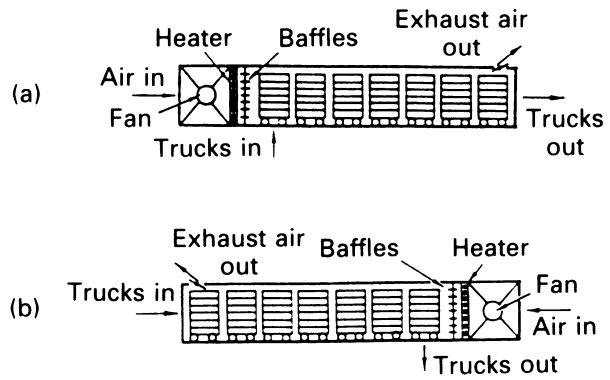


Figure 10.05. Tunnel dryer sketches showing (a) parallel and (b) counter flow operation (from Brennan et al. 1990).

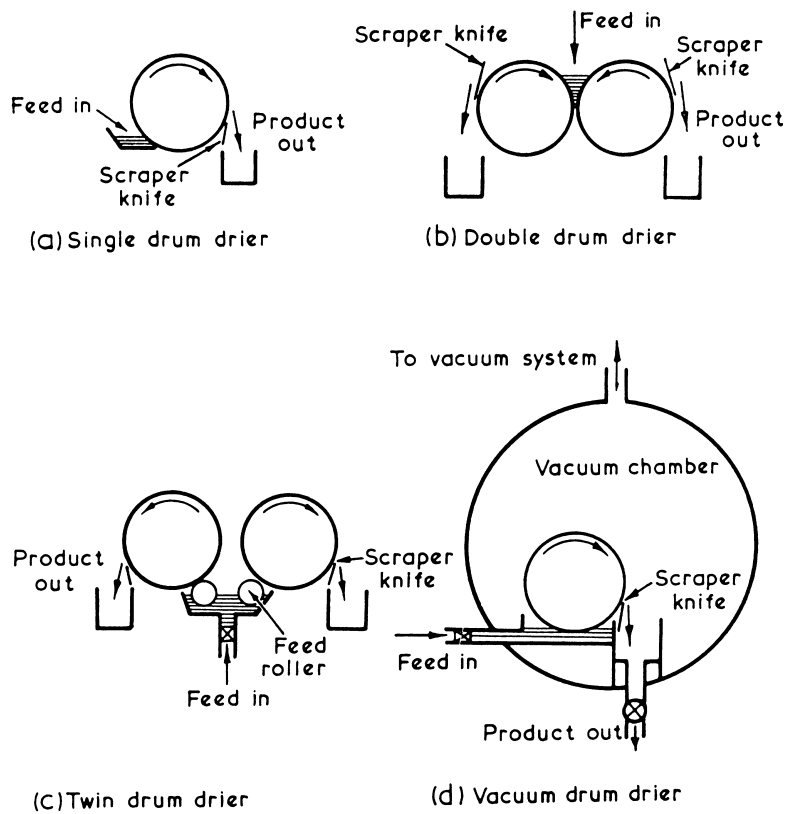


Figure 10.06. Different drum dryer configurations (from Brennan et al. 1990).

10.6.5 Other Drying

Numerous other air drying techniques are also used. The major function of all such systems is to move air over the product in such a manner that the product is dried as economically as possible without damage.

10.7 Special Drying Methods

10.7.1 Spray Drying

Spray drying is used to dry liquid products. The product to be dried is sprayed into a stream of heated air. Water evaporates into the air leaving the dry particles to be collected. The two major operations of concern in spray drying are droplet atomization and powder collection. To optimize drying, droplets should be small and uniform in size. Thus special procedures must be used to insure that atomization is satisfactory.

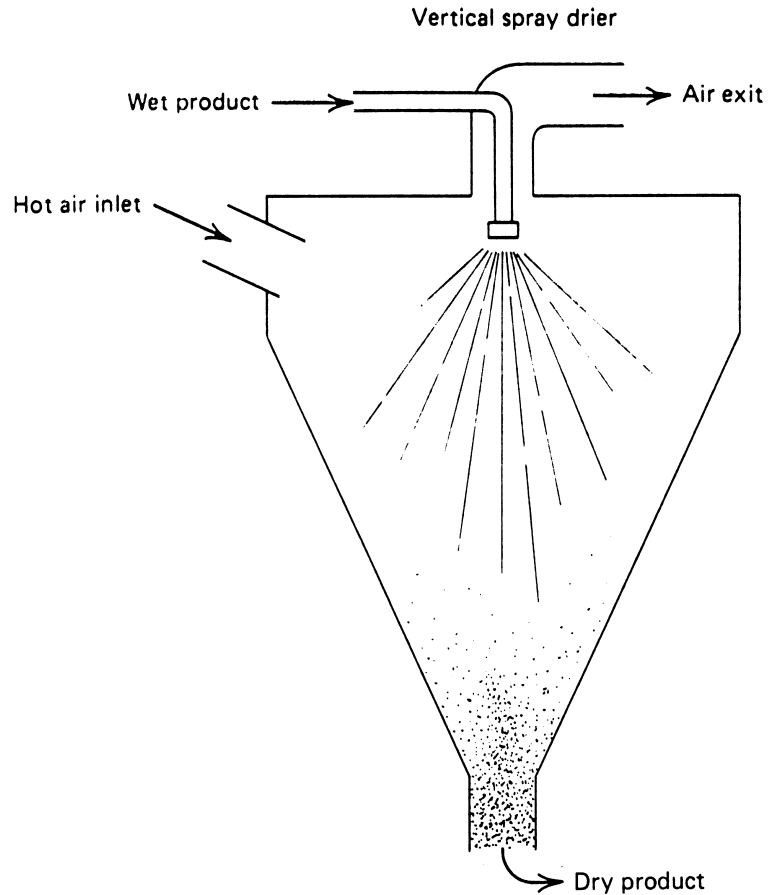


Figure 10.07. Spray dryer illustration.
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Collection of the dried powder also requires special techniques. The powder particles are small and move easily within an air stream. Collection chambers or special filters are normally used. Figure 10.07 shows a simple representation of a spray dryer. Actual operations are more complex, and many different configurations are available.

10.7.2 Vacuum Drying

In vacuum drying, the product is placed inside a chamber where the pressure is reduced to produce a vacuum. Since the total pressure in the chamber is very low, the partial pressure of the water vapor in the chamber is also very low. This low partial pressure causes a large partial pressure difference between the water in the product and the surroundings. Thus water moves more readily from the product to the surrounding environment in the chamber. Drying under vacuum conditions permits drying at a lower temperature. This characteristic of vacuum drying is very important for products that may suffer significant flavor changes at higher temperatures.

10.7.3 Freeze Drying

Freeze drying involves the removal of moisture from a frozen product without thawing that product. The temperature must be below freezing for that product (to insure that the product remains frozen) and the vapor pressure must be maintained at a very low level to permit moisture removal by sublimation. Because of the low temperature, low pressure, and low drying rate, freeze drying is quite expensive compared to many other drying methods. However, freeze drying can produce high quality dried products. Thus, it is the preferred drying method for some high value materials. Figure 10.08 shows a representation of a freeze dryer. "Freezer burn," sometimes seen in frozen foods, is an example of undesirable freeze drying. This very slow type of freeze drying can occur when inadequately protected food is stored in a freezer for extended periods.

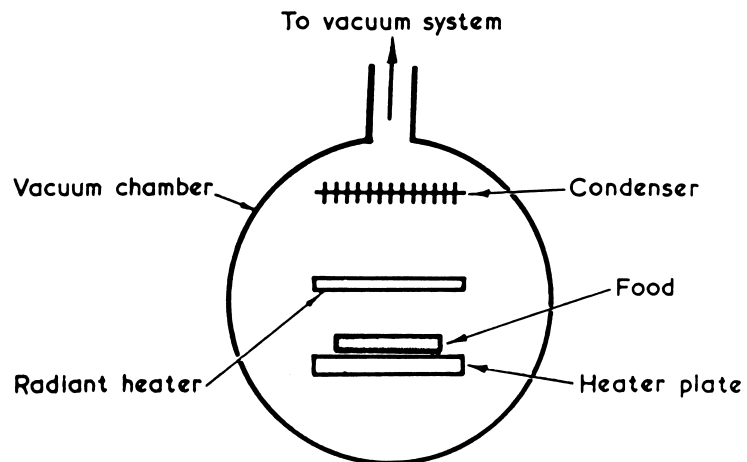


Figure 10.08. Representation of freeze drying components. Low temperature and pressure are required. (From Brennan et al. 1990.)

Example 10.3

A counter flow dryer unit uses heated air to dry apple slices. The slices enter at a rate of 200 kg/h and a moisture content of $m_1 = 0.9$. The “dried” slices have a moisture content of $M_2 = 0.10$. The drying air enters at 50°C and exits at 25°C and 90% relative humidity.

- (1) Find the water removed, \dot{m}_{wrem} , kg/h.
- (2) Find the entering air flow rate, m^3/min .

Solution:

Analysis of this problem requires calculation of mass balances for dry matter, water, and dry air. We begin by calculating the amount of dry matter (solids) and water entering and leaving with the slices. Since we know the moisture content and the input rate, we can determine the amount of water and dry matter in the entering slices:

$$m_1 = 0.9 = \frac{\dot{m}_{w1}}{\dot{m}_{T1}} = \frac{\dot{m}_{w1}}{200} \quad \text{giving} \quad \dot{m}_{w1} = 200 \times 0.90 = 180 \frac{\text{kg H}_2\text{O}}{\text{h}}$$

Next solve for the entering dry matter. Since only water is removed, the dry matter in the “dried” product is the same as that entering in the undried slices:

$$\dot{m}_{D1} = \dot{m}_{T1} - \dot{m}_{w1} = 200 - 180 = 20 \frac{\text{kg DM}}{\text{h}} = \dot{m}_{D2}$$

Knowing the moisture content and the amount of dry matter in the “dried” slices, we can now calculate the output rate of the product:

$$M_2 = \frac{\dot{m}_{w2}}{\dot{m}_{D2}} = 0.10 = \frac{\dot{m}_{w2}}{20} \quad \text{giving} \quad \dot{m}_{w2} = 20 \times 0.10 = 2.0 \frac{\text{kg H}_2\text{O}}{\text{h}}$$

The water removed from the apple slices is then:

$$\dot{m}_{wrem} = \dot{m}_{w1} - \dot{m}_{w2} = 180 - 2 = 178 \frac{\text{kg H}_2\text{O}}{\text{h}} \quad \text{ANSWER 1}$$

We know that the drying air follows a constant wet-bulb process as it gains moisture from the apple sliced. Using the temperature and humidity of the exit air, we can go to a psychrometric chart, find the wet-bulb temperature, and follow the constant wet-bulb line to the inlet air temperature. Using this process we find the following air properties:

Location	t_{db} (°C)	t_{wb} (°C)	ϕ (%)	v ($\text{m}^3/\text{kg DA}$)	W (g $\text{H}_2\text{O}/\text{kg DA}$)
Entering	50	23.7		0.925	7.7
Exiting	25	23.7	90		18

For use in our solution, we need to convert the humidity ratio to units of kg H₂O/kg DA (divide the table values by 1000).

We can now calculate the moisture gained by each unit mass of dry air:

$$\Delta W = W_1 - W_2 = 0.018 - 0.007 = 0.0103 \frac{\text{kg H}_2\text{O}}{\text{kg DA}}$$

Knowing the total water gain by the air and the gain by each kilogram of the air, we can now calculate the air flow rate:

$$\dot{m}_{DA} = \frac{178 \frac{\text{kg H}_2\text{O}}{\text{h}}}{0.0103 \frac{\text{kg H}_2\text{O}}{\text{kg DA}}} = 17\,280 \frac{\text{kg DA}}{\text{h}} = 288 \frac{\text{kg DA}}{\text{min}}$$

Using the calculated mass flow rate and the entering air specific volume from the psychrometric chart, and listed in the table above, we can determine the volumetric air flow rate:

$$\dot{Q} = 288 \frac{\text{kg DA}}{\text{min}} \times 0.925 \frac{\text{m}^3}{\text{kg DA}} = 266 \frac{\text{m}^3}{\text{min}} \quad \text{ANSWER 2}$$

Example 10.4

Repeat Example 10.3 with all parameter values the same except that the “dried” slices exit at a moisture content of $m_2 = 0.10$ (wet basis instead of dry basis).

Solution:

We follow a solution process very similar to that of the previous example. Input parameters are exactly the same as before. Thus:

$$\dot{m}_{D1} = \dot{m}_{D2} = 200 - 180 = 20 \frac{\text{kg DM}}{\text{h}}$$

Solving for the water in the “dried” slices:

$$m_2 = 0.10 = \frac{\dot{m}_{w2}}{\dot{m}_{T2}} = \frac{\dot{m}_{w2}}{\dot{m}_{w2} + \dot{m}_{D2}} = \frac{\dot{m}_{w2}}{\dot{m}_{w2} + 20}$$

$$0.1\dot{m}_{w2} + 2 = \dot{m}_{w2} \quad \Rightarrow \quad \dot{m}_{w2} = 2.22 \frac{\text{kg H}_2\text{O}}{\text{h}}$$

The moisture removed is then:

$$\dot{m}_{wrem} = \dot{m}_{w1} - \dot{m}_{w2} = 180 - 2.22 = 177.78 \frac{\text{kg H}_2\text{O}}{\text{h}} \quad \text{ANSWER}$$

Continuing as in the previous example, we find:

$$\dot{m}_{DA} = 287.7 \frac{\text{kg DA}}{\text{min}} \quad \text{and} \quad \dot{Q} = 266.1 \frac{\text{m}^3}{\text{min}} \quad \text{ANSWER}$$

Note that the results differ little between these two examples. That is because, at low moisture content, there is little difference between the wet basis and dry basis measurements. The difference would be much greater if an exit moisture content of 0.20 had been used in the examples.

10.8 Introduction to Evaporation

An important step in the production of many food products is the removal of water to produce a more concentrated liquid. The term used in the food industry to define this operation is **evaporation**. Examples of evaporated food products are evaporated milk, syrups, and various fruit juice concentrates. The basic principle involved in the evaporation process is the application of heat to evaporate free water present in the product. The configuration of the equipment used to accomplish this concentration defines the evaporator type.

10.8.1 Open (Atmospheric) and Vacuum Evaporators

The earliest evaporators were open kettles or pans placed over an open flame. Maple syrup, sweet sorghum syrup, and sugar cane syrup were produced using open evaporators during the early history of the United States. Figure 10.09 shows a sketch of an open pan evaporator used for sorghum syrup evaporation during the early 1900s (Walton et al., 1938). Evaporators very similar to that shown in Figure 10.09 continue to be used by many sorghum syrup producers in the United States. The primary difference is that few processors use wood as a heat source. Most now use gas (natural or LP) or steam as the direct heat source for their evaporators.

Two major disadvantages of open evaporators are higher operating temperatures and higher energy cost in comparison to vacuum evaporation systems. While acceptable for syrup production, the temperatures required to boil a product, thus evaporating water, are sufficient to produce undesirable flavors for many food products. In addition, such evaporation requires huge amounts of energy—more than 2200 kJ for every kilogram of water evaporated.

The problems noted above for open evaporators can be avoided by using vacuum evaporators. By evaporating at a lower pressure, the boiling point is lowered. This reduces the possibility of undesirable flavors. In addition, vacuum evaporators can be placed in series. These multiple effect evaporators use the vapor from one evaporator to provide energy for evaporation in the next evaporator in the series. This combination results in a significant reduction in energy use, although initial cost is greater.

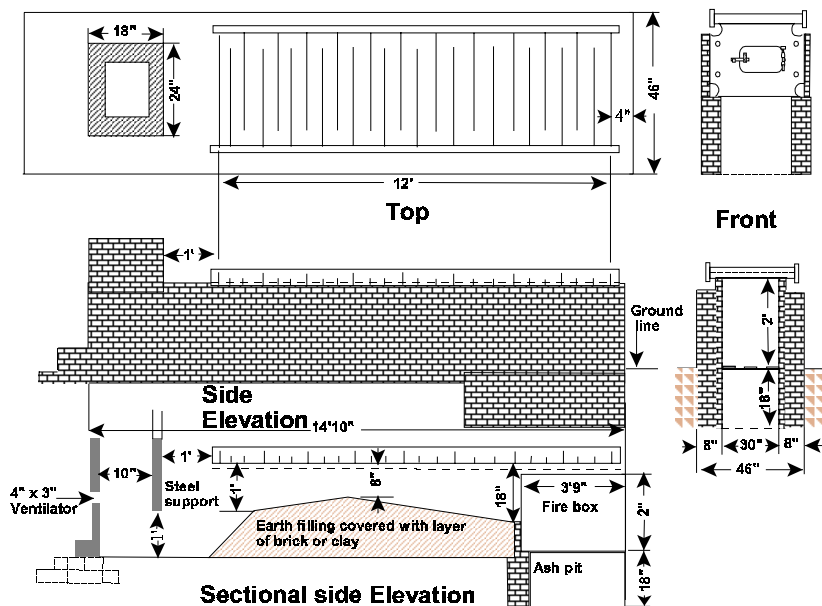


Figure 10.09. Open pan evaporator used for sorghum syrup evaporation (modified from Walton et al., 1938).

Example 10.5

A small open pan evaporator is used to produce sorghum syrup. Juice ($m = 0.87$ wb) enters at the rate of 800 kg/h. The finished syrup leaving the evaporator contains 80% solids. Five percent of the entering solids are removed as impurities during the evaporation process.

- (1) Find the production rate of the syrup (kg/h).
- (2) Find the mass of water removed per unit mass of syrup.
- (3) Find the energy required per hour to evaporate the water removed.
- (4) Find the steam flow required for evaporation if 20% of the heat is lost to surroundings. The steam enters at 350 kPa (saturated) and exits at a quality of 0.10.

Solution:

As with dryer analysis, the solution requires *mass* and *energy* balances. However, one unique difference from previous examples is that the dry matter mass balance must account for the solids removed. For the solids balance:

Solids (dry matter) entering (m_{DI}):

$$m_{w1} = 0.87 \times 800 = 696 \text{ kg H}_2\text{O/h}$$

$$m_{D1} = m_{T1} - m_{w1} = 800 - 696 = 104 \text{ kg DM/h}$$

$$(\text{or } m_{D1} = 0.13 \times 800 = 104)$$

Impurities removed are 5% of the entering solids, thus:

$$m_I = 0.05 \times m_{D1} = 0.05 \times 104 = 5.2 \text{ kg DM/h}$$

The solids remaining in the product are:

$$m_{D2} = m_{D1} - m_I = 104 - 5.2 = 98.8 \text{ kg DM/h}$$

$$\text{or } m_{D2} = m_{D1} - 0.5 \times m_{D1} = 0.95 \times m_{D1} = 0.95 (104) = 98.8$$

We can now determine the syrup output.

$$\text{For 80\% solids we can write the relationship as } 0.80 = \frac{\dot{m}_{D2}}{\dot{m}_{T2}}$$

$$\text{Thus, } \dot{m}_{T2} = \frac{\dot{m}_{D2}}{0.80} = \frac{98.8}{0.80} = 123.5 \frac{\text{kg product}}{\text{h}} \quad \text{ANSWER 1}$$

The amount of water in the product can now be determined as:

$$\dot{m}_{w2} = \dot{m}_{T2} - \dot{m}_{D2} = 123.5 - 98.8 = 24.7 \frac{\text{kg H}_2\text{O}}{\text{h}}$$

Knowing the water input (m_{w1}) and water output (m_{w2}), we can now determine the water removed:

$$\dot{m}_{wrem} = \dot{m}_{w1} - \dot{m}_{w2} = 696 - 24.7 = 671.3 \frac{\text{kg H}_2\text{O}}{\text{h}}$$

Converting to water removed per unit mass of syrup, we have:

$$\frac{\dot{m}_{wrem}}{\dot{m}_{T2}} = \frac{671.3}{123.5} = 5.44 \frac{\text{kg H}_2\text{O}}{\text{kg syrup}} \quad \text{ANSWER 2}$$

We can use the latent heat of the evaporated water to determine the energy needed for evaporation. Assuming an average evaporation temperature of 105°C we find that $h_{fg} = 2244 \text{ kJ/kg}$.

$$\text{Thus, } \dot{Q} = 2244 \text{ kJ/kg} \times 671.3 \text{ kg/h} = 1\,506\,400 \text{ kJ/h} = \underline{418.4 \text{ kW}}$$

ANSWER 3

We can now compute the required steam flow. The energy output per unit mass (kg) of steam is:

$$\begin{aligned} \Delta h_s &= h_g - [h_f + x h_{fg}] = 2731.6 - [584.3 + 0.1 \times 2147.7] \\ &= 2731.6 - 799. = 1932.6 \text{ kJ/kg steam} \end{aligned}$$

Knowing the energy required for evaporation (\dot{Q}) and the energy per unit mass

of steam (Δh_s), we can solve for the required steam flow \dot{m}_s :

$$\dot{m}_s \times \Delta h_s = \dot{m}_s [1932.6 \text{ kJ/kg steam}] = \dot{Q} = 1\,506\,400 \text{ kJ/h}$$

$$\dot{m}_s = 1\,506\,400 / 1932.6 = 779.5 \text{ kg steam/h (with no losses)}$$

Taking the 20% loss into account the above value represents only 80% of the required flow rate. Thus the required total steam flow rate is:

$$\dot{m}_{sT} = \frac{\dot{m}_s}{0.80} = \frac{779.5}{0.80} = 974.3 \frac{\text{kg steam}}{\text{h}} \quad \text{ANSWER 4}$$

10.8.2 Controlling Factors for Evaporation

Analysis of evaporator systems is relatively complex. In addition to the normal mass and energy balances that must be satisfied, other thermodynamic parameters must also be considered. These include boiling point and latent heat of vaporization of the raw and finished products. The boiling point of any liquid increases as pressure increases. Thus, vacuum evaporators, which operate below atmospheric pressure, require lower operating temperatures than those required for the same product in an open evaporator. The presence of sugars and/or other components in the liquid being concentrated increases the boiling point of that material at any given pressure. As the concentration of the liquid increases, so does the boiling point. This increase in boiling point is commonly referred to as **boiling point rise**. It is a function of the amount and type of constituents in the liquid. The combination of evaporator pressure and boiling point rise must be considered in determining the actual boiling point in the evaporator.

The latent heat of vaporization (h_{fg}) is the energy required to evaporate a unit mass of liquid at its boiling point. The value of h_{fg} for water at atmospheric pressure is 2257 kJ/kg; however, it does not remain constant as the boiling point changes. It decreases slightly as the boiling point increases. At any evaporator pressure (and boiling point), h_{fg} is quite large. Thus, substantial energy is required for evaporation processes.

Because h_{fg} of food products is large, evaporators require substantial amounts of energy input. This energy must be transferred from the energy source (commonly steam) to the liquid being evaporated. Thus, the heat transfer rate must be as great as possible in the heat exchanger area of the evaporator. This is a major consideration in evaporator design. In addition, foaming of the product and fouling of the heat exchanger surface can have significant adverse effects upon the heat transfer rate. Foaming occurs during concentration of some food products. This can substantially reduce the surface heat transfer coefficient (and the rate of heat transfer from the heat exchanger surface to the fluid.) Fouling of the heat transfer surface can create added resistance to heat flow, thus reducing the heat transfer rate.

Properties of raw material and finished product are major factors that enter into evaporator design and selection. Maximum temperature and length of time exposed to that temperature are significant in determining product quality for some products. Evaporators must therefore operate within specified temperature limitations and yet

allow for rapid evaporation. Viscosity is another important parameter since more viscous fluids tend to have higher boiling points and lower heat transfer rates.

10.8.3 Multiple Effect Evaporators

To reduce overall energy costs, evaporators may be placed in series such that the vapor from one evaporator is the heat source to evaporate water from the next unit in the series. Figure 10.10 shows how evaporators could be connected to provide a multiple effect system. In this system steam for evaporation is required for the first unit only. The latent heat of vaporization of the condensing steam provides energy to evaporate water in the first stage of the evaporator. Vapor from this stage is condensed in the next effect to vaporize the water there. This continues through all effects. Because we recycle the vapor into subsequent evaporator stages, we could make the following gross estimate of energy requirements: “in a multiple effect system, one kilogram of steam input will evaporate as many kilograms of water as there are effects.” This would imply that for a triple effect system, one kilogram of steam would produce three kilograms of vapor. This simplification is an aid in showing the advantage of multiple effects, but it gives a misleading (high) indication of the vapor produced. Aside from inefficiencies and heat losses, the latent heat of vaporization of water is not constant. It increases as the boiling point decreases. Thus, at every effect in the system, less vapor is evaporated in the current effect than was condensed from the previous effect.

The system shown in Figure 10.10 is called a forward feed system. The heat source and the product being concentrated flow in parallel. In this system, the pressure and temperature decrease with each effect. This decrease is necessary to permit use of vapor from one effect as the heat source for the next effect. The vapor can only be used if the boiling point in the next effect is lower. The boiling point can only be lower if the pressure is lower; thus, $P_1 > P_2 > P_3$ and $T_1 > T_2 > T_3$. An advantage of this system is that flow between effects occurs because of the pressure differences.

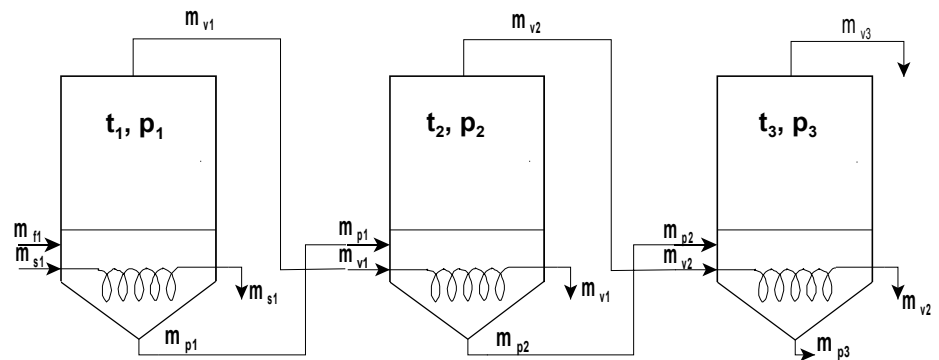


Figure 10.10. Multiple effect (three effects) forward feed evaporator system.

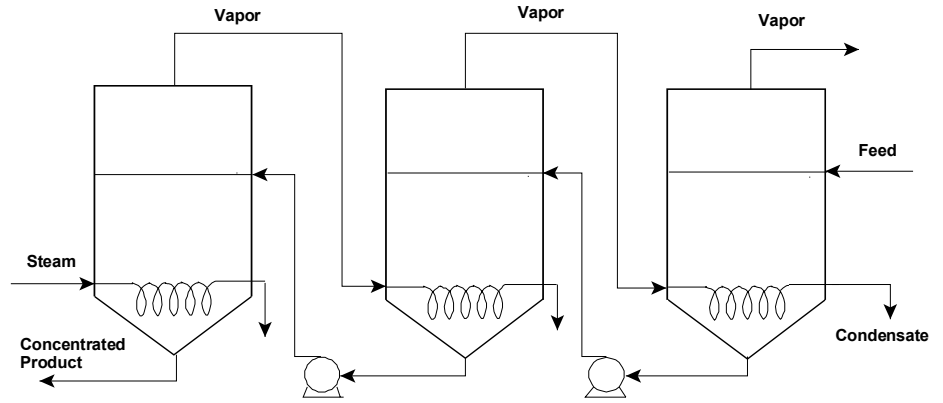


Figure 10.11. Backward feed multiple effect evaporator.

A different multiple effect arrangement, a backward flow system, is shown in Figure 10.11. Here, the product being concentrated flows counter to the flow of vapor used as the heat source. The number of effects (evaporators in the series) may vary depending upon the application. Economy is usually the controlling factor. Steam costs are a major component of operating costs and multiple effects significantly reduce steam requirements. However, the increased efficiency of more effects is eventually offset by the increased initial and maintenance costs of the added effects.

10.8.4 Mass and Energy Balances

Mass and energy balances are key components in analyses of any evaporator system. For multiple effect systems, this results in multiple equations that must be solved. Such an analysis is beyond the scope of our study. We will only examine a simplified analysis of a single effect system following the notation of Figure 10.12. The feed, product, vapor, and steam flow rates are represented by subscripts as indicated. Similarly, mass ratios of solids in the feed and product streams are X_f and X_p , respectively.

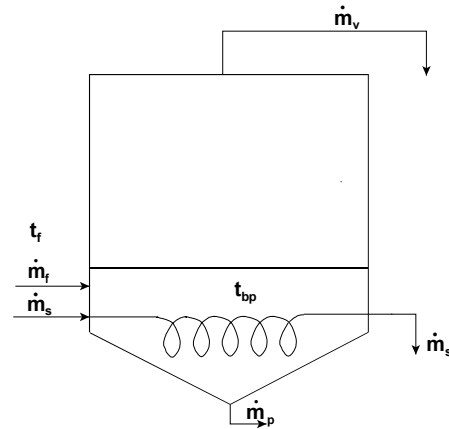


Figure 10.12. Notation for analysis of a single effect evaporator.

A total mass balance for this system gives the equation:

$$\dot{m}_f = \dot{m}_p + \dot{m}_v \quad (10.08)$$

A similar analysis of the solids balance gives:

$$\dot{m}_f X_f = \dot{m}_p X_p \quad (10.09)$$

And a water balance gives:

$$\dot{m}_f (1 - X_f) = \dot{m}_p (1 - X_p) + \dot{m}_v \quad (10.10)$$

Entering and exiting steam flow rates will be equal. The required magnitude of this flow is a function of the flow rate of feed material and the amount of water evaporated. An energy analysis is necessary to determine the steam flow required.

The energy balance analysis is somewhat more complicated. We will simplify the analysis by assuming that the evaporator is perfectly insulated. Thus, all energy from the steam is used to heat the feedstock to the boiling point and then evaporate the desired amount of water. An overall energy balance then becomes:

$$\dot{m}_s \Delta h_s = \dot{m}_s c_{pf} (t_{bp} - t_f) + \dot{m}_v \Delta h_{fs} \quad (10.11)$$

Example 10.6

A single-effect evaporator is used to concentrate syrup from 10% to 70% solids. The production rate is 50 kg/h. The evaporation occurs at a pressure of 50 kPa (a boiling point of 81.3°C for pure water). The feed syrup enters at a temperature of 20°C. Energy for evaporation is provided by steam entering as saturated vapor at 200 kPa and exiting as saturated liquid at the same pressure. What steam flow is required to accomplish the evaporation if we assume no energy losses?

Solution:

We must first perform a mass balance to determine the amount of water evaporated. Performing a solids balance (Equation 10.09) we have:

$$0.1 \dot{m}_f = 0.7 \dot{m}_p = 0.7(50 \text{ kg/h}) = 35 \text{ kg/h}$$

$$\dot{m}_f = 350 \text{ kg/h}$$

Then, solving for \dot{m}_v using Equation 10.10:

$$\dot{m}_v = 350(1 - 0.1) - 50(1 - 0.7) = 350(0.9) - 50(0.3) = 300 \text{ kg/h}$$

or by using Equation 10.08:

$$\dot{m}_v = \dot{m}_f + \dot{m}_p = 350 - 50 = 300 \text{ kg/h}$$

Knowing the amount of water evaporated in the concentration process, we can now determine the energy required to heat the feedstock to the boiling point and evaporate the water. The boiling point of a sugar solution is a function of pressure, sugar content, and type(s) of sugar present. The boiling point rise is less than 1°C at relatively low sugar concentrations and increases rapidly at concentration above 70% (Pancoast and Junk, 1980). At a concentration of 70% the boiling point rise would be near 5°C for a sucrose solution. For simplicity, we will ignore the increase in boiling point temperature as the syrup is concentrated and use 82°C as the approximate boiling point temperature of a 10% sugar solution at 50 kPa. This is a 0.7°C increase above the boiling point of pure water.

We analyze the energy balance using Equation 10.11, which states that:

$$\text{Steam Energy} = \text{Energy for Heating} + \text{Energy for Evaporation}$$

From steam tables:

$$\text{at } 200 \text{ kPa, } h_{fg} = 2201.6 \text{ kJ/kg (for condensing steam)}$$

$$\text{at } 82^\circ\text{C, } h_{fg} = 2303.8 \text{ kJ/kg (for boiling solution)}$$

We now have all parameters needed for a solution of Equation 10.11 except for the specific heat c_{pf} . At 82°C water has a specific heat of 4.2 kJ/kg K, and a 10% sucrose solution has a specific heat that is 95% of that for pure water. Thus:

$$c_{pf} = 4.2(0.95) = 3.99 \text{ kJ/kg K.}$$

Substituting into Equation 10.11, we find:

$$\dot{m}_s \times 2201.6 = 350 \times 3.99(82 - 20) + 300 \times 2303.8 = 86\,583 + 691\,140 = 777\,723$$

$$\dot{m}_s = \underline{353.2 \text{ kg/h}}$$

ANSWER

Note that the energy for evaporation is almost eight times larger than the energy required to heat the solution from 20°C to 82°C. Thus, energy for evaporation is the primary energy factor in evaporator systems; and our act of ignoring the boiling point rise had little effect upon the answer obtained.

List of Symbols

a_w	water activity, decimal
c_p	specific heat capacity at constant pressure, J/(kg K) or kJ/(kg K)
C, N, K	equilibrium moisture equation constants (see Tables 10.01 and 10.02).
EMC	equilibrium moisture content, decimal or percent
ERH	equilibrium relative humidity, decimal or percent
h_{fg}	$(h_f - h_g)$, latent heat of vaporization, kJ/kg
m	mass, kg
m	moisture content wet basis (wb), decimal or percent
M	moisture content dry basis (db), decimal or percent
M_e	equilibrium moisture content (db), decimal or percent
\dot{m}	mass flow rate, kg/s
P	pressure, kPa
rh	relative humidity, decimal or percent
t	temperature, °C
T	absolute temperature, K
X	mass ratio (mass fraction), decimal
ϕ	relative humidity, decimal or percent
Subscripts	
bp	boiling point
d	dry
f	feed
p	product
rem	removed
s	steam, saturation
t	total
v	vapor
w	water
wb	wet-bulb
ws	water at saturation

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Problems

- 10.1. Show the relationship between moisture content wet basis (m) and dry basis (M) by plotting M as a function of m for values of m between 0 and 0.95.
- 10.2. Show how the equation used to solve for M_e in Example 10.2 can be obtained from Equation 10.06.
- 10.3. Air at 75°C (167°F) and a dew point temperature of 20°C (68°F) is used to dry apple leather in a counter flow arrangement. The air leaves at 90% relative humidity. The leather enters at a rate of 100 kg/hr and 85% moisture (wb). The dried product contains 20% moisture (wb).
 - a. How much dried product is produced per hour?
 - b. How much water is removed hourly?
 - c. What air flow rate is needed to accomplish the drying?
- 10.4. Repeat problem 10.3, assuming a finished product of 25% moisture (wb).
- 10.5. Repeat problem 10.3, assuming a finished product with 0.2 kg H₂O/kg of dry matter.
- 10.6. Mashed potatoes at 40% moisture content (wb) are to be air dried to 12% moisture. The output rate is 500 kg/hr of the 12% moisture content (wb) product. The drying air enters at 55°C and 10% relative humidity and is removed at 80% relative humidity.
 - a. Find the moisture content of the potatoes on a dry basis before and after drying.
 - b. What is the water removal rate, kg/hr?
 - c. What is the temperature of the exiting air?

- d. Find the volumetric flow rate of the inlet air.
- e. If the drying air was heated from an initial temperature of 27°C, what was its initial relative humidity?
- 10.7. Sliced apples at 88% moisture (wb) are to be dried to 25% moisture in a counter flow dryer. Drying air enters at 90°C (194°F) and 34°C (93°F) wet bulb. If the air leaves at 60% relative humidity, what air flow rate is required to dry 1000 kg/hr (2200 lb/hr) of sliced apples?
- 10.8. A small, steam heated, open pan evaporator is used to produce sorghum syrup. In the process, 8 kg of juice produces 1 kg of syrup. The production rate is 100 kg/hr of syrup that contains 76% solids. Five percent of the solids in the raw juice is removed as impurities during the process.
- How many kilograms of water are removed per kilogram of syrup?.
 - Find the juice supply rate needed to maintain the production rate.
 - How much energy is required per hour to evaporate the water?
 - What steam flow is required if saturated steam is supplied at 350 kPa and leaves at 10% quality? (Assume that 20% of the energy from the steam is lost.)
- 10.9. The equilibrium moisture content of some materials is related to relative humidity by the following equation:

$$1 - \phi = \exp[-K(t + C)M_e^N]$$

- where C , K , and N are constants for a given material, t is the temperature (°C), N is the relative humidity (decimal), and M_e is the equilibrium moisture content (% dry basis). Values of constants for selected materials are given in Table 10.01. Plot the equilibrium moisture content as a function of relative humidity for any one of these products at temperatures of 0°C, 10°C, 30°C, and 50°C.
- 10.10. An evaporator is used to concentrate juice of sugar cane to produce syrup. Complete the table below for the various combinations of juice input, juice sugar content, syrup production and syrup sugar content. The sugar content is expressed in °Brix, which represents the percent sugars present in the solution.

Condition	Juice		Syrup	
	Input (kg/h)	° Brix	° Brix	Output (kg/h)
A	1000	15°	70°	
B	1000	15°		150
C		15°	65°	300
D	1000		70°	100