4
Dehydration

Robert H. Driscoll
School of Chemical Engineering, The University of New South Wales, Sydney, Australia

4.1 Introduction
Dehydration is the removal of water from a product, and is an important unit operation in the food industry. A wide range of dryer types exists, including freeze dryers and fluidized bed dryers, allowing the method of drying to be tailored to a specific product. The reasons for drying are to preserve the product, modify product texture, and reduce transport weight.

The most important of these is preservation, or more precisely extension of shelf life. This is achieved by reducing moisture to a level at which its availability for reactions is reduced, measured by a parameter called product water activity. This fundamental property of a product is related to, but not the same as, moisture content and has a precise chemical definition. As moisture in the product is reduced, the water activity of the product is also reduced. In this way, deterioration reactions are slowed down and the product will last longer.

However, removal of moisture comes at a cost. Drying is expensive, since the energy required to remove water is high. Heat recovery systems (for example, heat pumps) may be used to reduce this cost, but these have higher capital costs and added complexity.

In this chapter, we will consider first the science of moisture movement within the product and its relationship to quality. Then by studying the interaction of the product with air, methods for predicting rate of drying will be developed. Finally, technologies available for drying will be discussed.

4.2 Drying and food quality
Dehydration may change a food product in several ways. The taste, texture, and aroma (called the organoleptic qualities) may be affected, and the heat required for drying may cause chemical reactions such as denaturation of proteins. Drying also affects the physical parameters of the product, as removal of water causes shrinkage (plums become prunes, grapes become raisins). Due to these changes, rehydration after drying may not restore the original product.

4.2.1 Deterioration reactions in foods
Water activity ($a_w$) is a measure of the availability of water to partake in chemical reactions. Formally, it is defined as the ratio of the water vapor pressure ($p_v$) in a food to that of pure water vapor ($p_s$) at the same temperature:

$$a_w = \frac{p_v}{p_s} \quad (4.1)$$

Water activity can be measured by determining the relative humidity in the headspace above a product in a sealed container. During drying, the fraction of chemically bound water within the product increases, reducing the vapor pressure. Consequently, there is less free water available for chemical and microbial reactions.

Note that changing moisture content is a means to control water activity, and therefore it is water activity, not moisture content, which is of first importance in drying. Every product has a unique characteristic relationship between moisture content and water activity, and so the safe moisture content will be different for each product. Grains may be dried to 12–14% moisture, but peanuts and oilseeds must be dried to under 10% for the similar shelf life.

4.2.1.1 Microbial stability
The limits of microbial growth are determined by water activity. For example, most bacteria need $a_w > 0.91$, and
molds need $a_w > 0.70$. The exact water activity limit for a specific organism also depends on factors such as pH, oxygen availability, the nature of solutes present, nutrient availability, and temperature. Generally, the less favorable the factors, the higher the value of $a_w$ required for growth.

The effect of microbial action on quality may simply be economic loss, for example discoloration, physical damage, off-flavors and off-odors (spoilage microbes), or may be a food safety issue, for example with pathogens which cause food-borne diseases. Reduction in $a_w$ will increase the microbiological stability of the product, thus increasing shelf life.

4.2.1.2 Chemical stability

Water may take part in chemical reactions as
- a solvent, providing a transport mechanism for reactants to come in contact with each other
- a reactant, as a component consumed in the reaction
- a product, for example, in non-enzymatic browning reactions, or
- a modifier, for example by catalyzing or inhibiting reactions.

During drying, reactions continue until a critical $a_w$ is reached. Drying temperature has an important effect on the rates of chemical reactions, so directly affects the quality of the dried product. A small change in temperature can cause a large change in reaction rate. Higher temperatures also provide energy for a greater range of reactions.

Reactions that depend on moisture to bring reactants together will become increasingly limited during dehydration, due to the reduced molecular mobility of the reactants.

At low moistures, a further preservation mechanism becomes significant. As product moisture drops, solutes become more concentrated and therefore solution viscosity rises. This makes it increasingly difficult for reactants to come together.

Some examples of important food chemical reactions include the following.
- **Enzymatic reactions**, which are not completely understood, but which are very slow at low $a_w$ values, due to lack of mobility of the substrate to diffuse to the active site of the enzyme.
- **Non-enzymatic browning** (NEB), a water-dependent reaction with maximum reaction rates around $a_w = 0.6–0.7$. Water is also a reaction product. Too much water inhibits the reaction by dilution, too little gives inadequate mobility.
- **Lipid oxidation**, a reaction that is fast at both low and high values of $a_w$, slow at intermediate values.
- **Loss of nutrients**, for example vitamin B or C losses due to breakdown at high temperatures.
- **Loss of volatiles**, for example flavors and aromas, from the product.
- **Release of structural water**, which changes food texture.

4.2.1.3 Physical stability

Microbiological and chemical stability both correlate with water activity, but physical deterioration correlates with moisture content. Some examples of physical effects include the following.
- **Softening** of texture at high moisture, hardening at low moisture (water acts as a plasticizer of the food material).
- **Differential shrinkage**: outer layers shrink relative to inner layers, leading to either surface cracks or radial cracks.
- **Surface wetting effects**: moisture works on the product surface to expand pores and capillaries.
- **Case hardening**: a hydrophobic layer may be formed in oil-rich or proteinaceous products during rapid drying of outer layers, which traps moisture inside the product.
- **Cell collapse**: cells may collapse if internal moisture is removed, leading to the product shrinking and the surface becoming wrinkled, for example in prunes or sultanas.

4.3 Hot air drying

Most food dryers use heated air passed across a product to remove moisture. Commercially, moisture is normally used as an indication of the progress of drying. However, from the preservation point of view, it is not moisture but water activity which must be controlled.

Air holds a relatively small amount of moisture, normally less than 1% by mass. We can define a relative humidity for the air, which is the ratio of the actual vapor pressure ($p_v$) to the maximum possible vapor pressure ($p_s$) at the same temperature. Saturated air has a relative humidity of 1, often written as 100%.

Relative humidity ($r$) is a measure of the water activity of the air. If a product sample is allowed to equilibrate with a small amount of air in a sealed container, then the air and the product will equilibrate with respect to both temperature and moisture. At equilibrium, the air...
Relative humidity is numerically equal to the product water activity:

\[ r = \frac{p_v}{p_s} = a_w \]  \hspace{1cm} (4.2)

If a food product comes in contact with air with \( r > a_w \) then it will absorb moisture from the air. Here are some important consequences.

• A product should be stored in a package or a storage environment where the relative humidity is controlled.
• Drying cannot reduce the product water activity below the relative humidity of the air used for drying the product.

Water activity can be controlled by methods other than dehydration. A common method in the food industry is to add humectants, which are chemicals such as sugars, salts and glycerol which bind available water. Freezing a product also reduces the available water for reaction.

Since water activity determines product shelf life, we should dry to a specific water activity. Commercially, however, product drying is based on moisture content, and this can lead to unsafe storage practice. A dryer operator might incorrectly assume that a moisture content that is safe for one product is safe for a second similar product. This may not be valid. In the next section, the relationship between moisture and water activity will be explored.

### 4.3.1 Product equilibrium

If we place some product in a jar (Figure 4.1) and then seal the jar, the product and air will come to equilibrium over time. There are two forms of equilibrium occurring here: a thermal equilibrium, where the temperatures equalize, and a mass (or moisture) equilibrium. Mass equilibrium occurs when the rate of evaporation from the surface of the product becomes equal to the rate of condensation. At this point, the equilibrium relative humidity (ERH) is controlled by the product equilibrium moisture (EMC) and temperature only. By measuring the ERH at different moisture contents, but keeping the temperature constant, a product isotherm can be constructed.

Product isotherms represent an important basic property of food products, and help in determining safe storage moistures.

### 4.3.2 Moisture content definitions

The concentration of water in a product is called the product moisture content. This may be measured in two ways.

• The mass of water divided by the total product mass (wet basis, wb).
• The mass of water divided by the dry solids only (dry basis, db).

Both definitions are commonly used.

For example, for a product containing 40 kg of water for every 100 kg, the moisture content is expressed as 40% on a wet basis. Since the mass of dry solids is 60 kg, this is equivalent to 40/60 or 67% dry basis.

Using the symbol \( W \) for wet basis moisture and \( M \) for dry basis moisture:

\[ M = \frac{m_w}{m_w + m_s} \quad W = \frac{m_w}{m_s} \]  \hspace{1cm} (4.3)

where \( m_w \) is the mass of water and \( m_s \) is the dry solids mass in a sample. For example:

• 200 g of water per kg of product is 20% wet basis moisture content.
• 200 g of water in 800 kg dry solids is 25% dry basis moisture content.

To convert from wet basis to dry basis:

\[ M = \frac{W}{1-W} \]  \hspace{1cm} (4.4)

• 20% wb is equal to 25% db moisture content.
• 75% wb is 300% db moisture content (which means three parts water to one part dry solids).

To help you understand this concept, exercises 1 and 2 are included.

#### 4.3.2.1 Exercise 1

Using the conversion formulae above, complete the following table.

<table>
<thead>
<tr>
<th>Evaporation</th>
<th>Condensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Air</td>
</tr>
</tbody>
</table>

**Figure 4.1** Product in a sealed glass jar.
<table>
<thead>
<tr>
<th>Total mass product (kg)</th>
<th>Dry product mass (kg)</th>
<th>Dry basis moisture content (%)</th>
<th>Wet basis moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>50</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>100</td>
<td>–</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>–</td>
<td>50</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>–</td>
<td>20</td>
<td>–</td>
<td>85</td>
</tr>
</tbody>
</table>

What is the maximum possible wet basis moisture content? Can dry basis moisture content be over 100%?

Let $m_p$ be the initial mass of a product. If we dry the product from an initial moisture content of $W_o$ to $W_f$ (both wet basis), then a useful formula for calculating the mass of water removed is:

$$m_w = m_p \times \frac{(W_f - W_o)}{(1 - W_o)} \quad (4.5)$$

4.3.2.2 Exercise 2

How much moisture would I need to remove to dry 100 kg of wet product from 50% to 20% wb?

4.3.3 Evaporation of water

Moisture is removed by evaporation from the surface of a product. Water vapor moves through a boundary layer into a moving air stream that carries the moisture away. The driving force for diffusion through the boundary layer is the difference in vapor pressure between surface moisture and the air. The energy required to evaporate product water must be replaced by heat transferred to the product surface.

4.3.4 Important psychrometric equations

Psychrometry is a branch of physical chemistry that is concerned with the properties of a gas–vapor mixture. The terms “gas” and “vapor” refer to the natural state of a substance at room temperature. For drying, we are concerned with a particular mixture, which is air and its contained water vapor. The gas component is nitrogen, oxygen, and other trace elements, and has an average molecular weight of 29.0 kg/kmol. The term “vapor” refers to the water component, since water is normally a liquid at room temperature.

Both the gas and vapor components are assumed to obey the ideal gas equation which is:

$$PV = nRT_K \quad (4.6)$$

where $P$ is absolute pressure (Pa), $n$ is number of moles, $R$ is the universal gas constant (8.314 kJ/kmol.K) and $T_K$ is absolute temperature. The total pressure is the sum of the partial pressures exerted by each component in the gas mixture:

$$p_t = \sum_{i=1}^{n} p_i \quad (4.7)$$

where subscript $t$ indicates total pressure and subscript $i$ refers to the $i^{th}$ component of a mixture of $n$ components.

Two basic properties of an air-vapor mixture are its temperature (as measured by a dry bulb thermometer) and its moisture content, which is defined in exactly the same way as the proportion of water in a product, and is called the absolute humidity, $H$:

$$H = \frac{m_w}{m_a} \quad (4.8)$$

where $m_w$ is the weight of water, $m_a$ is the weight of the dry (non-water) air components. The units for absolute humidity may be written as kg/kg d.a. (kilograms per kilogram of dry air), since by convention, air humidity is measured on a dry basis.

Dry bulb temperature $T$ and absolute humidity $H$ are often chosen as the two principal axes for a chart of air-vapor properties, called a psychrometric chart (see Figure 4.7).

Curved lines represent air relative humidity, varying from 0 (for the $H = 0$ axis) up to 1.0 (the vapor saturation line). Air that contains more moisture than the saturation line is unstable, and will separate into condensate and saturated air.

The total heat content of the air is called enthalpy, and includes both sensible and latent heat. When measured relative to the natural state of its components at 0°C, the air enthalpy is:

$$h = m_a[c_a T + H(c_v T + \lambda_0)] \quad (4.9)$$

where $c_a$ is the dry air specific heat, $c_v$ is the specific heat of water vapor (kJ/kg·K), $T$ is air temperature (Celsius), and $\lambda_o$ is the latent heat of evaporation of pure water at 0°C. The three components for a mass of air $m_a$ are:

- sensible heat of the dry air, $m_a c_a T$
- sensible heat of the water held in the air, $m_w H c_v T$
- latent heat of the water held in the air, $m_w H \lambda_o$. 64 Food Processing: Principles and Applications
Exercise 3 has been included to allow you to practice these concepts.

4.3.4.1 Exercise 3

1. Locate the point 20 °C, 10 g/kg on a psychrometric chart. Then use the chart to find the enthalpy per unit mass of this point.

2. The specific heat of dry air is 1.01 kJ/kg·K, of water vapor is 1.83 kJ/kg·K, of liquid water is 4.18 kJ/kg·K, and the latent heat of water at 0 °C is 2501 kJ/kg (values at 20 °C). From this information, calculate the heat per kg of each term in Equation 4.9 at a temperature of 20 °C and a humidity of 10 g/kg dry air.

3. Compare your answers to parts 1 and 2. They should be in agreement!

Air can carry very little water vapor, and so the value of air humidity, H, is of the order of 10–20 g of water per kg of dry air. Thus, the second term in Equation 4.9 makes little contribution to the total enthalpy. However, since water has a very high latent heat of evaporation, the last term is substantial.

Now we can add lines of constant enthalpy to the psychrometric chart. These lines have a negative slope, and are parallel to the wet bulb temperature lines. The enthalpy lines are useful for representing drying.

4.3.5 Wet bulb temperature

If we place a glass thermometer in an air stream, the temperature measured is called the dry bulb temperature. If the bulb of the thermometer is kept wet, for example with a cotton wick, evaporation of water cools the bulb and the indicated temperature is called the wet bulb temperature (Figure 4.2). Wet bulb temperature is a convenient practical method for determining the amount of moisture in the air.

The rate of heat flow into the cotton wick is given by the convective heat transfer equation:

$$\dot{q} = h_c A (T - T_{wb})$$  \hspace{1cm} (4.10)

where $h_c$ is the heat transfer coefficient (W/m²·K). By analogy to convective heat transfer, the rate of evaporation $\dot{m}_c$ is written as:

$$\dot{m}_c = k_y A (H_s - H)$$  \hspace{1cm} (4.11)

where $A$ is the area (in m²) for evaporation of moisture from the wick, and $k_y$ is the mass transfer coefficient in kg/m²·s. $H_s$ is the saturation humidity of the air at the temperature of the air, and $\lambda_T$ is the latent heat of free water at the evaporation temperature $T$ (in °C).

At equilibrium:

$$\dot{q} = \dot{m}_c \lambda_T$$  \hspace{1cm} (4.12)

Thus:

$$T - T_{wb} = \frac{k_y \lambda_T}{h_c} (H_s - H)$$  \hspace{1cm} (4.13)

Equation 4.13 is very close to a linear relationship between $H$ and $T$, called the wet bulb line, and this line can be plotted on a psychrometric chart. The lines are not perfectly straight, as changes in the value of $\lambda_T$ with temperature cause small variations from linearity.

Drying is an isoenthalpic process, which means that the heat energy lost from the air to the product equals the heat energy gained by the air by evaporation of moisture from the product. It is common to represent drying processes using constant enthalpy lines on a psychrometric chart. For mixtures of air and water, these lines are very close to the wet bulb temperature lines given by the above equation.

A complete psychrometric chart is given in Appendix A. The following simple drying problem illustrates the use of a psychrometric chart.

4.3.5.1 Problem

Air at 25 °C, 40% RH is being used to dry a 5 ton bed of rice at 20% wb moisture. Estimate how much air is required to dry the rice to 14% db, if the air leaves at 84% RH, in equilibrium with the grain.

4.3.5.2 Solution

From the psychrometric chart, the inlet air wet bulb temperature is
Appendix A: Psychrometric chart, SI units, at one atmosphere pressure.
As the air leaves the dryer at 84%, we can trace along the wet bulb line for 16.2 °C, until the air relative humidity is 84%. This point is at 18 °C. Now read off the inlet air moisture content:

\( H_{in} = 0.008 \text{ kg/kg d.a.} \)

For the outlet air moisture content:

\[ H_{out} = 0.011 \text{ kg/kg d.a.} \]

Dry mass = 5000 kg × 80% = 4000.0 kg

Initial moisture = 5000 kg × 10% = 1000.0 kg

Final moisture = 14% × 4000 kg = 560.0 kg

\( .\) weight of moisture to remove = 440.0 kg

air required = 440/(0.011–0.008) = 1470 kg

Note use of wet basis when total mass is used, and dry basis when solids mass is used as the reference quantity.

### 4.4 Drying theory

In this section we will develop a basic theory for food drying.

#### 4.4.1 Important moisture definitions

It is convenient to define the moisture in a product in terms of how easy it is to remove this water, as shown in Figure 4.3.

- **Equilibrium moisture content** (EMC) is the moisture level at which a product is in equilibrium with the moisture of its surrounding air.
- **Free moisture** is moisture in excess of the equilibrium moisture content, so can be removed by drying. Further moisture cannot be removed without reducing the air relative humidity, and hence changing the product equilibrium moisture content.
- **Unbound moisture** is moisture in excess of a minimum level (called the critical moisture content) required for the product to exhibit a water activity of 1. Thus, a product with unbound moisture will dry at the same rate as a free water surface, and at a constant rate.
- **Bound moisture** is moisture less than the critical moisture content, so exerts a lower vapor pressure than the saturation vapor pressure. As a result, the product water activity is less than 1 if the product moisture is less than the critical moisture content.

#### 4.4.2 Vapor adsorption theories

Moisture moves through a product to its outer surface, and then evaporates to an air boundary layer. Each water molecule must then diffuse through the air boundary before it is carried away by the air stream. This complete process is called desorption. The opposite process, in which water condenses onto the surface, is called adsorption, and the movement of water into the product from the surface is called absorption.

Models have been proposed to explain adsorption and desorption, leading to equations predicting the water content/water activity equilibrium of the product. At constant temperature, this product-dependent relationship is called an isotherm.

- **Langmuir** (1918). Langmuir studied the bonding of the first water molecules condensing onto a dry product surface (monolayer adsorption), by equating the rate of evaporation at the surface to the rate of condensation. This model describes the shape of the isotherm at low moistures only. Subsequent theoretical models used Langmuir’s model as a starting point.
- **Brunauer, Emmett, and Teller** (BET model) (1938). The BET model was the next major theoretical development, as it extended Langmuir adsorption to multilayer adsorption, summing the contribution of additional layers of moisture. This model results in a typical sigmoidal curve, as commonly found in food products, but only works well up to about 40% RH.
- **Guggenheim-Anderson-deBoer** (GAB model). In recent times, a third major step forward was made with the GAB model, which was developed independently by three researchers, and gives good agreement over the full isotherm curve for most products.

Over the years, many other models have been developed, mostly empirical. Since the GAB model describes product
behavior well, and has a theoretical basis, it has been increasingly applied within the food industry. The constants required for the equation are determined experimentally by placing samples in jars containing saturated salts, and measuring the equilibrium state between the air in the jar and the product sample. The full equation requires six constants.

- **The monomolecular moisture content**, which is the minimum amount of moisture required to occupy all of the surface sites of the product with a single layer of water molecules.
- Two constants related to **equilibration rates** between adsorption and desorption.
- Three **activation energies** which describe the effect of temperature.

It is possible that the large number of constants have helped contribute to the success of the model in describing food product equilibrium characteristics. Nevertheless, the model has achieved general acceptance in the drying community.

### 4.4.3 Hysteresis

We might assume that drying a product surface is simply the inverse of wetting a surface, so that a plot of the desorption isotherm should look the same as an absorption isotherm, but this is not the case. As moisture adsorbs to the product surface, the energy released may modify the surface structure, affecting the way water molecules bond to the surface. This causes an effect called **hysteresis** in which desorption isotherms differ from absorption isotherms. Hysteresis decreases after successive cycling of the product between low and high moisture (see Figure 4.4).

### 4.4.4 Theory of moisture movement within a product

Before moisture can evaporate from the surface, it must diffuse to the product surface. There are several possible diffusion mechanisms.

- **Liquid diffusion**, where moisture moves through the product in proportion to the liquid water gradient at any point. This is expressed well by Fick’s equation for diffusion.
- **Vapor diffusion**, which assumes that the product is porous, so that vapor can move through connected pores within the material.

### 4.4.5 The four drying rate periods

The rate at which a thin layer of product dries is an important characteristic. The thin layer drying rate is defined as the rate of water removal from a layer of product that is sufficiently thin that the air leaving the layer is not detectably different from the inlet air. In more practical terms, the entire product encounters identical drying conditions.

The opposite to thin layer drying is deep bed drying, where successive layers of the product encounter air that has interacted with previous layers. A deep bed can be modeled as a succession of thin layers, by equating the exit air from each layer with the inlet to the next layer. Thus, a deep bed does not dry evenly. All dryers can be categorized as either thin layer or deep bed dryers.

Plotting moisture against time for a thin layer gives the drying curve for the product (Figure 4.5). For a high moisture product, we can identify four distinct drying regions.

1. **Initial transient region**: the product equilibrates with the wet bulb temperature of the air, by either evaporation of surface moisture (if the product is initially hotter than the drying air wet bulb temperature) or condensation (if the product starts cooler).
2. **Constant rate region**: during constant rate drying, the process can be modeled using the wet bulb equation:
where \( t \) is drying time, \( M \) is the sample moisture content (db), \( m_s \) is the dry solids weight of the sample (kg), and other symbols are as defined for the wet bulb temperature equation. During this period, the product dries at the same rate as a free water surface.

3. **Transitional region**: dry spots start to appear on the surface at the critical moisture content \( M_c \), so that the product no longer behaves like a free water surface, and diffusion of moisture from within the product starts to limit moisture loss at the surface.

4. **Falling rate region**: once the drying surface no longer has unbound water, moisture removal is limited by diffusion from inside the product:

\[
\frac{\partial M}{\partial t} = D(T) \frac{\partial^2 M}{\partial x^2} \tag{4.15}
\]

Equation 4.15 is called Fick’s law of diffusion, and the moisture content \( M \) is a function of position \( x \) and time \( t \). Variation in moisture content within the product causes moisture gradients resulting in moisture movement. The constant \( D \) is called the product mass diffusivity and is a measure of how quickly moisture will diffuse through different materials. The diffusivity is affected by temperature, \( T \).

Figure 4.5 shows a thin layer drying curve. \( M_o \) is the initial moisture, \( M_c \) is called the critical moisture and \( M_e \) is the asymptotic equilibrium moisture between the air and product.

The initial transient region is only significant for a short time near the start of drying. During this time, the enthalpy of the product equilibrates with the enthalpy of the air, by changing the product temperature. This does not mean that the air and product come to the same temperature, since surface evaporation is occurring, but that the rate of heat flow into the product (by convection) equalizes with the heat loss by evaporation, exactly as in the wet bulb situation described earlier. This effect can be observed by placing very cold tomatoes into a preheated oven for a very short time (less than a minute), and observing the condensation on the surface. It is also the mechanism for removing heat that we observe when we cool by sweating during exercise!

The constant rate period (from \( M_o \) to \( M_c \)) is a straight line on a plot of time against moisture (measured on a dry basis). This period is only observed for high-moisture products such as slurries, where the water activity equals 1. Only products with a water activity of 1 will exhibit a constant rate region, and they will dry at the air wet bulb temperature until the critical moisture content is reached. Few food products exhibit a constant rate region.

The transition region occurs around \( M_c \). This region (where the surface starts to dry) is difficult to model and so is not normally included. As a result, many studies of drying use the falling rate period to model the complete drying curve.

The remainder of the curve represents the falling rate period. Many authors divide this into two regions, noting that there seems to be an initial fast falling rate period, and subsequently a slower period leading to equilibration between the air and the product.

### 4.4.6 Representation of drying on a psychrometric chart

Thin layer drying can be represented on a psychrometric chart (Figure 4.6). The product entering the dryer is plotted according to its temperature and equilibrium relative humidity (point P in Figure 4.6). For example, if the product is at 20°C and has a water activity of 0.95, then P is the intersection of the 20°C temperature line and the 95% relative humidity line.

In a dryer, the inlet air is conditioned to be hotter and drier than the product, normally by heating the air (point I in Figure 4.6). The drying process can be represented by a line drawn through the inlet air point at constant enthalpy towards the air saturation line, intersecting with the product relative humidity line (point B).
The curve PB (at constant relative humidity) represents the initial transient region. The line BI (at constant enthalpy) is the falling rate region. If the product enters the dryer with a water activity of 1, then point B represents the constant rate period, and the initial transient will be located on the air saturation line.

This method of presenting drying using a psychrometric chart allows for a deeper appreciation of the two regions most relevant to foods: the initial transient and the falling rate period. By plotting the thin layer drying curve on the chart, useful information on the exit air properties can be calculated directly. Note also that the initial transient can be seen as essentially an enthalpy equilibration between the product and the drying air, and the falling rate period as a water activity equilibration.

### 4.4.7 Models of the falling rate period

Fick’s diffusion equation can be solved for simple regular shapes, homogeneous product, and constant drying conditions (Crank, 1970), resulting in equations of the form:

\[
M(x, t) = a_0 + \sum_{n=1}^{\infty} d_n \exp a_n x. \exp b_n t
\]  \hspace{1cm} (4.16)

where \(a_n, b_n\) and \(d_n\) are constants. Generally we need only the average moisture content of the product:

\[
M(t) = c_0 + c_1 \exp -k_1 t + c_2 \exp -k_2 t + \cdots
\]  \hspace{1cm} (4.17)

where \(c_n\) and \(k_n\) are constants dependent on product shape and inlet air properties, and \(k_n\) is related to the mass diffusivity of the product. This is called a multicomartment model.

The simplest useful form of this equation is to keep the first two terms only:

\[
M = c_0 + c_1 \exp -k_1 t
\]

Substituting \(M = M_0\) at \(t = 0\) and \(M = M_e\) at \(t = \infty\) gives:

\[
\frac{(M - M_e)}{(M_0 - M_e)} = MR = e^{-k_1 t}
\]  \hspace{1cm} (4.18)

where \(MR\) is called the moisture ratio, and varies from 1 to 0 during drying. If a constant rate period exists, then time \(t\) refers to time after the critical moisture is reached, and \(M_0\) is replaced with \(M_c\).

Differentiating Equation 4.18 gives:

\[
\frac{\partial M}{\partial t} = -k_1 (M - M_e)
\]  \hspace{1cm} (4.19)

where \(k_1\) is a drying rate constant in reciprocal time units, showing that the drying rate is proportional to the difference between the present product moisture and its final equilibrium moisture. In many cases, this single term model may be sufficient for predicting product drying times.

The following problems will illustrate solution techniques for the constant rate period and the falling rate period.

#### 4.4.7.1 Example problem for the constant rate period

A 4 m² tray is filled with a liquid product with a density of 1000 kg/m³, to a depth of 7 mm. The product has an initial solids content of 8%, and dries at a rate of 420 g/min. The critical moisture content, marking the end of the constant rate period, is 133% db, after which the drying rate of
product starts to fall. Find the drying rate in the constant rate period in terms of moisture content.

4.4.7.2 Solution

Initial weight of product (density × volume) is

\[ 4 \text{ m}^3 \times (7 \times 10^{-3} \text{ m}) \times 1000 \text{ kg/m}^3 = 28 \text{ kg}. \]

Since 8% of this is solids, the product dry weight is:

\[ 28 \text{ kg} \times 0.08 = 2.24 \text{ kg}. \]

The drying rate is given as 420 g/min or 0.42 kg/min. From the definition of dry basis moisture content, the drying rate in terms of moisture content is:

\[ 0.42 \text{ kg/min} / 2.24 \text{ kg} = 18.8\% \text{ db/min}. \]

4.4.7.3 Example problem for the falling rate period

A product has a drying rate constant \( k_1 \) of 1/120 min\(^{-1}\). Calculate the time to dry from 60% to 10% db if the equilibrium moisture content is 4% db.

4.4.7.4 Solution

Solve Equation 4.18 for time:

\[ t = (-1/k_1) \ln MR \]

\[ \therefore t = -120 \ln [(10 - 4) / (60 - 4)] = 268 \text{ min} = 4 \text{ h 28 min}. \]

4.4.8 A complete drying model

For products where the constant rate region is significant (such as slurries and pastes), the drying rate for the constant rate period can be represented by a single constant, \( k_0 \). Combining the constant rate and falling rate models gives a simple overall model:

\[ \text{For } M \geq M_c : \quad \frac{dM}{dt} = -k_0 \]

\[ \text{For } M < M_c : \quad \frac{dM}{dt} = -k_1(M-M_c) \quad (4.20) \]

4.4.9 Effect of airflow

The drying models presented above (Equations 4.14 and 4.18) assume that there is adequate airflow to remove moisture from the product surface. At low air speeds, the capacity of the air to hold moisture limits the drying rate. Thus for limited airflow, the rate of moisture removal is affected by air speed. Above a critical air speed, heat transfer becomes the rate-limiting step, and air speed has little effect on drying rate. Thus increasing fan power does not necessarily improve the drying rate. This is true for both the constant rate and falling rate periods. As a result, there is little point in increasing drying air speed above this critical level for a thin layer.

However, experimentally a small increase in the rate of drying is observed above the critical air speed, where the rate of drying increases roughly with the cube root of air speed. This small effect is due to an increase in the convective heat transfer coefficient from the air to the product surface as air speed increases, caused by reducing the air boundary layer thickness adjacent to the product.

For deep bed or cross-flow drying, air speed has a major effect on the total drying rate, as the air spends a greater time in contact with the product. Under these conditions, drying capacity is affected strongly by the rate of air supply to the dryer.

4.5 Drying equipment

There is a large range of types of dryers, including drum, rotary, tray, cabinet, vacuum, osmotic, spray, column, and freeze dryers. Dryer designs are selected based on the particular needs of the product requiring drying. Liquids are often partially predried in evaporators to reduce the load on the dryer.

Dryers may be categorized by the following characteristics.

- **Mode of operation**: batch means that the dryer is loaded, operated and the dried product unloaded. Continuous means that the dryer is loaded and unloaded continuously during operation.

- **Method of heating**: direct heating means that the flue gases from combustion come in contact with the product; indirect heating means that a heat exchanger is used to transfer heat from the flue gases to the drying air, thus protecting the product from possible contaminants. Heating may also be achieved by electricity, for example air resistance heaters, or by steam. The product may also be directly heated by electricity without air, for example by conduction, infrared, microwave or radiofrequency, but these methods are beyond the scope of this chapter.

- **Nature of product**: product might be loaded into the dryer as solid, liquid, slurry or granules, each requiring a different form of dryer. Liquids can be dried in spray
dryers, solids on meshes, granular materials in deep beds or fluidized beds, and slurries in trays.  
- **Direction of airflow:** the drying air may be **co-current, counter-current or cross-flow**. A dryer may have zones with different airflow directions (combination dryers). In the following section, dryers have been classified as batch or continuous, and the continuous dryers further classified by the direction of airflow.

### 4.5.1 Batch dryers

Batch dryers are often simpler in design than continuous dryers, but can be difficult to connect with continuous processing lines. In addition, the time required for loading/unloading will reduce the effective time of utilization of the dryer. So batch dryers tend to be used for small-scale production such as rapidly changing product lines, pilot plant processing, rural production, and high-value products.

**Kiln dryers** are a simple, universal form of dryer used for drying thin layers of product. The term “kiln” refers to a temperature-controlled chamber. A kiln dryer normally consists of a drying tray over some form of heat source, for example a biomass combustor or a furnace, and so are direct-fired. They are inefficient, as the hot air, after passing through a single layer of product, is vented to atmosphere. They are commonly used for drying sliced fruits and vegetables, including hops, apple slices, and pineapple rings.

**In-store dryers** (bin dryers) can both dry and store product (in a similar way as a cool room both cools and stores). The granular product is placed in bulk on a mesh supporting screen, and air is pumped into a plenum chamber below the product, passing through the screen and then through the product. These dryers have high thermal efficiency, as they operate at near ambient temperatures with the drying front submerged in the product mass for a large proportion of the drying time, so that the air leaves close to saturated. They are suitable for granular products such as grains and nuts.

There are many choices in the operation of an in-store dryer.  
- Layer drying, where 1–2 m of wet grains are loaded and partially dried, and then additional harvested grain is placed on top. This increases the efficiency of both the aeration system (increased airflow due to reduced flow resistance) and thermal efficiency (as the exit air now passes through new wet product and so is utilized to its maximum capacity).

- Mixing, for example by unloading a grain bin into a second bin via conveyors, an inexpensive operation which helps mix wet and dry product together. Not all products are suited to being mixed, as migration of moisture from wet grains to adjacent dry grains may cause fissuring (for example, with rice).

- Reverse flow, where the direction of aeration is periodically reversed in order to improve the uniformity of the final product, at the expense of slightly greater energy consumption, caused by moisture having a longer average path before it exits the dryer.

In-store dryers are especially suited to drying seed, as they operate most efficiently at low temperatures. Most seeds should not be heated over about 43°C in order to retain viability.

**Tray dryers** (cabinet dryers) require that the product is placed on trays in a closed cabinet. Air enters the dryer, is mixed with recirculated air, reheated, and passed across the trays. A proportion of the heated air is vented from the dryer in order to remove moisture. These dryers are suited to small-scale operations and allow for rapid changes in product line. By recirculating most of the air, heat losses are reduced and the energy efficiency greatly improved. They are very common in food plants, as they are able to handle most products including fruits and vegetables, liquids, fish, and pasta.

**Freeze dryers** use sublimation rather than evaporation of moisture. Sublimation is the process of direct conversion of ice to vapor, and requires about 2.8 MJ/kg of water. They are expensive, but are suitable for high-value, heat-labile products. The product is placed on heated shelves and the drying chamber evacuated. The effect of reducing the air pressure is to cause the product to cool by sublimation of moisture until the temperature is about –20°C to –40°C. Evaporative drying is slow at low temperatures, but sublimation drying is relatively fast. The low temperatures protect the product from changes due to heating and reduce the loss of volatiles such as aroma and flavor. In addition, the structure of the product is generally better preserved by freeze drying. Due to their high capital cost, freeze dryers are normally used for high-value products, such as starter cultures and coffee.

### 4.5.2 Continuous dryers

Continuous dryers are suited to running for long periods of time with the same product, and may be fitted with feedback controls to maintain drying conditions and/or product exit conditions.
4.5.2.1 Rotary dryers

A rotary dryer consists of a long cylinder, supported on girth rings that are used to rotate the dryer. Product is fed in at one end, and heated air comes in contact with the material as it passes down the cylinder, which is usually slightly inclined to allow the material to flow down. As the cylinder rotates, product may be picked up by flights mounted along the inside surface of the barrel, carried and then dropped, allowing good air-product contact and product mixing. The flights may be straight (aligned along the rotating cylinder) or helical.

The dryer is suited to granular products such as grains and pet food pellets. It may be direct- or indirect-fired, and may be run using either co- or counter-current airflow.

4.5.2.2 Drum dryers

A large range of drum dryer designs exists, but the essential feature is a steam-heated drum being coated with liquid product. As the drum rotates, a thin film of liquid is picked up on the surface of the drum. The thickness of this layer can be controlled by blades close to the drum surface or by a second rotating drum. In the time that the drum rotates, the thin product layer is dried to a solid and scraped off the surface as flakes. The drum dryer is suited to liquids, pastes and purees, such as baby foods, cooked starch slurries, breakfast cereals, vegetable and fruit pulps.

4.5.2.3 Spray dryers

Spray dryers create a fine spray of liquid product in a hot air environment. The liquid is pumped into a nozzle (preferably using a positive displacement pump to ensure a uniform flow of product), which forces the liquid through an atomizer, a device that imposes high shear stresses in the liquid. Examples of atomizers are:

- parallel concentric disks with one rotating, the other stationary. The liquid is forced between the two plates from an axial feed
- perforated plate: the liquid is forced under high pressure through small holes in the plate.

Both methods break the liquid into fine droplets, which assume a spherical shape owing to surface tension. As the liquid leaves the high shear region, it enters a hot air region, which may be designed co- or counter-currently to the product flow. At high temperatures the outside of the droplet dries quickly, forming a hard shell. Water inside the droplet boils, rupturing the hard shell to create distinctive partial shells or honeycombed patterns, depending on the product properties. This open structure leads to a powdered product that can be easily rehydrated.

The resulting mixture of dried product powder and air exits the dryer and is separated in a cyclone. In some cases, the product may be passed to a fluidized bed dryer to complete the drying process. Examples of products commonly dried in a spray dryer include milk and instant coffee.

Some spray-dried powders do not rehydrate very effectively, due to a process where a clump of powder is wetted on the surface, forming a layer that resists further wetting. To avoid this problem, spray-dried powders may be carefully rewetted (by about 15%) by a steam spray, which allows the powder to coalesce (combine) at a few junction points between the particles. The powder is then redried and sieved. The junction points survive, giving a larger particle structure yet without loss of surface area for rewetting (since the junction points are small). This process is called instantizing, because it allows the powder to be mixed and dissolve rapidly in water, and is commonly used with milk powders.

Since the feed must be atomized and each droplet dried, spray dryers tend to have a low capacity for drying for a given volume, compared with other forms of drying. Their success in the food industry is due to the adoption of predrying by means of evaporators. The evaporator is able to cope with large amounts of product, but requires that the product remains a liquid, preferably of low viscosity, whereas a spray dryer is not able to handle a large amount of liquid, but is perfect for the transition from liquid to solid. The two units, working in series, offer a perfect solution to the overall problem of drying large amounts of liquids to powder.

4.5.2.4 Fluidized bed dryers

Fluidized bed dryers are designed for granular solids such as small grains, powders, and pellets. The material to be dried is placed on a perforated screen, and air is blown through the screen at sufficient speed (typically over 2 m/sec) until the resulting pressure drop across the bed matches the total product weight, so that the product is suspended in the flow of air and behaves like a fluid. Further increases in air speed have little effect on the pressure drop across the bed. The product is successfully fluidizing when aeration cells form in the bed, wherein product and air mix uniformly.
The benefit of fluidization is that the product dries from all sides, creating a more uniform moisture distribution compared with conventional drying in a fixed bed, and reducing the thickness of the vapor boundary layer around the product, thus reducing drying time. The mixing process also encourages greater product moisture uniformity.

Care must be taken to ensure that the dryer design is suited to the specific product. The size, shape, and cohesiveness of the product significantly affect drying efficiency. Also, fluidized bed dryers are susceptible to dead pockets, areas where insufficient air is supplied to achieve particulate fluidization. The stagnant product collects, heats and becomes a contamination or fire hazard.

Large particles can often be successfully fluidized by entrainment with finer particles, reducing the average particle size to a range where fluidization works effectively.

Fluidized bed dryers were developed for the chemical engineering industry but, due to their small footprint, rapid surface drying, high throughput and uniformity of drying, are increasingly finding applications in the food industry. They can be operated as batch or continuous dryers.

4.5.2.5 Spouted bed dryers

These dryers operate on the same principle as a fluidized bed dryer, except that only a central core of product is fluidized; the remaining product forms an annular region around the central air spout. Product entrained in the spout is heated rapidly, before cascading out of the top of the spout and falling (the fountain region) back into the annular region. Since the outside annular region is also aerated, the heated product continues to dry as it falls through the annulus, before being guided back to the air spout.

A simple modification of the unit allows liquids to be dried. The drying chamber is first filled with inert spheres (for example, nylon) and the liquid product is sprayed into the chamber. The liquid coats the spheres, dries rapidly, and then breaks off due to impact between the spheres. The resulting powder is carried out by the air spout and can be collected using a cyclone separator.

Spouted bed dryers are potentially more energy efficient than fluidized bed dryers but in practice, problems with scale-up from design prototypes to full-scale units have limited their application to the food industry. There appear to be multiple problems with scale-up, including area to volume ratios and the height and stability of the spout.

Spouted bed dryers have been used for drying cereal grains such as wheat, and have successfully dried blood products and other food liquids.

4.5.2.6 Flash dryers

Flash dryers use very high air temperatures for very short residence times while the particles are pneumatically conveyed through the dryer. Thus, the main components of a flash dryer are a large fan and air heater, a cylindrical column through which the product rises with the heated air, a product feeder (such as an Archimedes screw or rotary star valve) to feed the product into the conveying air stream, and a separation unit (such as a cyclone separator) to collect the dried product. They differ from spray dryers in that they handle wet powders and slurries but not liquids. They are used for making dried powders, including drying dietary fiber, starch, casein, and dried gravy. Although the air temperature may be high (typically 150°C), the product residence time is only a few seconds and its temperature stays low.

4.5.2.7 Multistage (belt) dryers

A belt dryer consists of a drying tunnel and a continuous conveyor belt, which holds the product. For large particles, drying is a slow process, limited by the rate of moisture diffusion from the center of the product to the outside. For this reason, belt dryers are arranged in multiple stages, with the air conditions at each stage being chosen to give the best drying effect and least quality degradation. Often high temperatures are used in the early stages and low temperatures to finish the drying process. The product may take 3–9 hours to pass through the dryer, depending on the type of product and the degree of drying required.

The stages may be arranged sequentially, forming one long continuous dryer, or to save floor space, the belts may be positioned on top of each other, allowing product to tumble from one belt to the next. As it falls to the next belt, fresh product surfaces are exposed, accelerating the drying process.

4.5.2.8 Column dryers

Column dryers are suited to granular products such as corn, rice, and wheat. The central drying chamber is fed continuously with wet product from elevators or
buffer bins. The product falls slowly through the dryer as dried product is removed from the base. Hot air is introduced into the product mass through vents or a central air column. Often, a cooling section is used to arrest product thermal damage. The reason for choosing a column design is to save floor space (at the expense of height), in contrast to most dryer designs which take up large amounts of floor space.

Column dryers may be co-current, countercurrent or cross-flow, and modern column grain dryers are mixed flow, meaning that they utilize combinations of flow. Many products need to be dried slowly, for example products which exhibit case-hardening, become excessively brittle if dried quickly, or are so large that internal moisture migration dominates surface evaporation. In these cases tempering bins are often used with the column dryers. These bins collect the exit product and hold it for a period of several hours, allowing the moisture within the product to temper (become more uniform). Each pass through the dryer only removes a fraction of the total free moisture, yet the utilization of the dryer is improved.

### 4.6 Analysis of dryers

#### 4.6.1 Moisture and heat balances

Analysis of a kiln dryer provides a suitable starting point for dryer analysis (Figure 4.7). This is the simplest dryer configuration, where ambient air is heated in a furnace, then enters the drying chamber, interacts with the product, then exits the chamber.

For the following analysis, assume that the inlet air conditions remain constant. Equating the moisture change of the product to the difference between the inlet and outlet air moisture content gives:

\[ \dot{m}_a (H_I - H_E) = m_p \frac{\partial M}{\partial t} \]  

(4.21)

where \( \dot{m}_a \) is the airflow rate, \( H_I \) and \( H_E \) are the inlet and outlet absolute humidities, \( m_p \) is the mass of product in the dryer and \( \frac{\partial M}{\partial t} \) is the drying rate (dry basis), and is negative for drying.

![Figure 4.7](image.png)

Figure 4.7 Representation of a kiln dryer on a psychrometric chart.
If we know the temperature and relative humidity of both the inlet and outlet air (for example, by measuring them directly using thermometers and relative humidity meters), then we can use the psychrometric chart (see Figure 4.7, where the lines represent a kiln-drying process) to determine the inlet and exit absolute humidities.

4.6.1.1 Exercise 4

Using the psychrometric chart in Figure 4.7:

1. describe what happens to the product
2. describe what happens to the air.

Note that the exit air humidity $H_E$ will be somewhere between $H_I$ and $H_B$, the exact position depending on factors such as the airspeed and drying time.

Important points on the diagram are denoted by capital letters as follows: ambient air (point A), inlet air to the dryer (point I), exit air from the dryer (point E), initial product state (point P), and conditions after the initial transient (point B). In this diagram, note the following important lines.

- **Heating the air (line AI)**: ambient air is heated in the furnace to the required drying temperature.
- **Air and product interaction (line IE)**: the air picks up moisture from the product and exits the dryer.
- **Initial transient (line PB)**: the product and air come to thermal equilibration but not moisture equilibration.
- **Drying the product (line BI)**: the product dries on the tray. As the product dries, its water activity will drop and temperature rise, so the product state changes from B and moves towards I. The product may never reach equilibrium with the drying air, as the kiln dryer will be shut down when the product reaches the required moisture content.

For a dryer that incorporates air recirculation, we need to include an additional step – the mixing of the air exiting the chamber with ambient air. This requires both a mass and energy balance to calculate the combined mass flow and new air temperature. Graphically, mixtures can be represented on a psychrometric chart by straight lines joining the two components being mixed. The actual mixture point can then be determined by the mass proportion of components being mixed.

The following problem illustrates analysis of a dryer that recirculates air internally.

4.6.1.2 Problem using recirculation

A cabinet dryer circulates 30 kg/min dry air across a stack of 10 drying trays. Each tray holds 1 kg of product at 95% wb. If the ambient air is at 20°C and 8 g/kg d.a., and the exit air is at 50°C and 20 g/kg d.a., estimate:

i. the rate of moisture removal from the trays if the rate of internal air recirculation is 90%
ii. the heater size for the unit and
iii. time to dry in the constant rate period to 45% wb.

4.6.1.3 Solution

i. The amount of air exiting the dryer is:

$$10\% \times 30 \text{ kg/min} = 3 \text{ kg/min}.$$ 

Thus the rate of moisture removal is:

$$3 \text{ (kg/min)} \times (20 - 8)/1000 \times 60 \text{ (min/h)} = 2.16 \text{ kg/h}.$$ 

ii. To find the size of heater required, solve the air mixture equations to find the thermal difference between the air before the heater and the air leaving the heater. If I mix 90% of the exit air with 10% of the inlet air, then:

$$T_m = 90\% \times 50 + 10\% \times 20 = 47^\circ C$$

$$H_m = 90\% \times 20 + 10\% \times 8 = 18.8 \text{ g/kg}$$

where $T_m$ and $H_m$ are the mixture point temperature and absolute humidity.

From a psychrometric chart, the enthalpy of air at 47°C and 18.8 g/kg is 96 kJ/kg. Drawing an enthalpy line through the exit air conditions, locate the inlet conditions with the same enthalpy as the exit air (which is 102.3 kJ/kg) and the same absolute humidity as the mixture air (18.8 g/kg). The difference in enthalpy between these two points is (102.3 - 96) = 6.3 kJ/kg, and this heat must come from the air heater. Thus the required heater size is:

$$6.3 \text{ (kJ/kg)} \times 30 \text{ (kg/min)} \times (1/60) \text{ (min/sec)} = 3.15 \text{ kW}.$$ 

iii. The rate of moisture removal is:

$$30 \text{ kg/min} \times (20 - 18.8)/1000 = 0.036 \text{ kg/min}.$$ 

The amount of moisture to remove from each tray is:

$$1 \text{ kg} \times (1 - 0.95) \times (0.95/0.05 - 0.45/0.55) = 0.91 \text{ kg}.$$ 

The time required to remove 0.91 kg moisture from 10 trays is:

$$t = 10 \times 0.91/(0.036) = 252.5 \text{ min} = 4 \text{ h 12 min}.$$ 

So after about 4 hours, the product will enter the falling rate period.
We have analyzed two examples of dryers, the kiln dryer (no recirculation) and the tray dryer (which includes recirculation). The principles that were used to do this can be extended to cover many types of air dryers.

### 4.7 Sustainability

Dryers may consume up to a quarter of a nation’s energy budget (Mujumbdar, 2000) but continue to evolve rapidly in response to industry needs. Some of the pressures that generate changes in drying technology are environmental considerations, quality requirements, and processing innovations due to unit cost, space or time requirements.

Environmental considerations have become an increasingly important issue. Dryers require a high energy input, as the drying air must supply the heat required to evaporate water from the product. If the air passes through the product to the surrounding air, this heat energy is dispersed to the atmosphere. By recirculating the air, we can retain a proportion of the heat put into the air and so substantially reduce energy use. This may be done in several ways.

- Replacement of a small proportion of the air circulating within the dryer with ambient air (as was done with the tray dryer).
- Using a heat recovery system to dehumidify the air, based on refrigeration principles, a system which works best at low temperatures (20–40 °C).
- Chemical desorption of moisture from the exit with replenishment of the absorption material by some other form of drying (such as solar).

This results in less release of heat to the environment and a lower heating cost.

Energy reduction is not the only consideration, however, since there is also a demand for improved quality. The challenge then is to try to meet both objectives. This may be difficult; for example, vacuum and freeze drying allow dehydration at lower temperatures, retaining a greater fraction of the aroma and flavor compounds, but at a much higher equipment cost.

The demand for more economical, higher quality drying motivates technical innovation. New technologies being researched include the following.

- Transmission of energy by forms of electromagnetic radiation, for example radiofrequency drying which transmits the energy uniformly to moisture within the product, so decreasing drying time.
- Heat pump dryers, mentioned in section XXX, where the application of heat energy recycling reduces the energy cost of drying.
- Superheated steam drying.
- Pulse drying, where drying air speed and temperature are switched between low and high levels.
- Replacing heated air with heated granular solids as the heat transfer medium, for example using hot sand to dry a product.
- Combinations of drying technologies, such as fluidized drying combined with superheated steam or heated sand. Several drying methods have clear advantages in terms of reducing drying cost, especially in-store (or more generally near-ambient) drying and heat pumps. Other technologies offer marginal energy reductions, of the order of 10%, for example pulsed airflow. A number of technologies for improving thermal efficiency have become standard, including impingement drying and combined evaporator/spray/fluidized bed drying. A typical dryer from the 1970s might have a thermal efficiency of around 60%, whereas many modern technologies achieve efficiencies far greater than 100% by using heat recovery systems (such as the heat pump) or natural air drying capacity (for example, the deep bed dryer).

For a company trying to manufacture product in a competitive environment, reductions in energy may be less of an incentive than increasing throughput, since the processing cost is generally a small fraction of the total production cost, and also that margins on food products are generally low and so high production volumes are required. An improvement must satisfy both objectives to be successful – reduce energy but also allow high-volume drying. As the cost of energy increases, sustainable innovations become more appealing to the equipment purchaser.

### 4.8 Conclusion

In this chapter, we have considered some types of dryers and introduced the study of dryers. Dryer design is dependent on the nature of the product being dried, and a system that works for one product may not be satisfactory for others. Dryers also affect the quality of a product in many different ways, and so choices about temperature and handling inside a dryer are important.

By studying psychrometrics and drying theory, we can better understand how to choose or design a dryer that is suited to the product’s needs. Modeling the drying process allows us to estimate the time required for product drying under different conditions, and so choose a dryer capable of handling the required volume of product. We have looked at some simple models of product drying, which allow prediction of drying times and provide a better understanding of the basic processes involved.
References


Further reading


