CHAPTER 7

DRYING

Drying is one of the oldest methods of preserving food. Primitive societies practised the drying of meat and fish in the sun long before recorded history. Today the drying of foods is still important as a method of preservation. Dried foods can be stored for long periods without deterioration occurring. The principal reasons for this are that the microorganisms which cause food spoilage and decay are unable to grow and multiply in the absence of sufficient water and many of the enzymes which promote undesired changes in the chemical composition of the food cannot function without water.

Preservation is the principal reason for drying, but drying can also occur in conjunction with other processing. For example in the baking of bread, application of heat expands gases, changes the structure of the protein and starch and dries the loaf. Losses of moisture may also occur when they are not desired, for example during curing of cheese and in the fresh or frozen storage of meat, and in innumerable other moist food products during holding in air.

Drying of foods implies the removal of water from the food. In most cases, drying is accomplished by vaporizing the water that is contained in the food, and to do this the latent heat of vaporization must be supplied. There are, thus, two important process-controlling factors that enter into the unit operation of drying:

(a) transfer of heat to provide the necessary latent heat of vaporization,
(b) movement of water or water vapour through the food material and then away from it to effect separation of water from food.

Drying processes fall into three categories:

- Air and contact drying under atmospheric pressure. In air and contact drying, heat is transferred through the foodstuff either from heated air or from heated surfaces. The water vapour is removed with the air.
- Vacuum drying. In vacuum drying, advantage is taken of the fact that evaporation of water occurs more readily at lower pressures than at higher ones. Heat transfer in vacuum drying is generally by conduction, sometimes by radiation.
- Freeze drying. In freeze drying, the water vapour is sublimed off frozen food. The food structure is better maintained under these conditions. Suitable temperatures and pressures must be established in the dryer to ensure that sublimation occurs.

Three States of Water

Pure water can exist in three states, solid, liquid and vapour. The state in which it is at any time depends on the temperature and pressure conditions and it is possible to illustrate this on a phase diagram, as in Fig. 7.1.

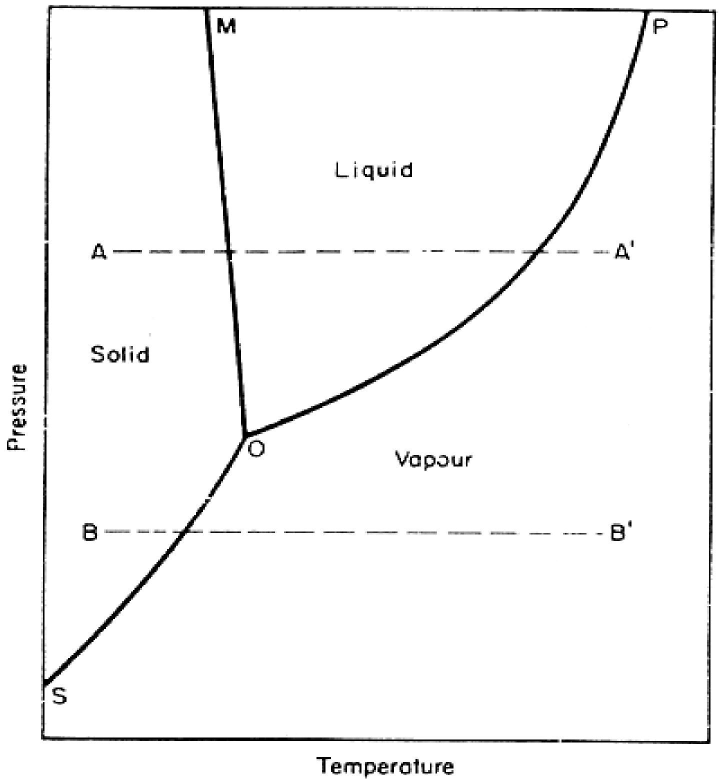

Figure 7.1 Phase diagram for water

If we choose any condition of temperature and pressure and find the corresponding point on the diagram, this point will lie, in general, in one of the three labelled regions, solid, liquid, or gas. This will give the state of the water under the chosen conditions.

Under certain conditions, two states may exist side by side, and such conditions are found only along the lines of the diagram. Under one condition, all three states may exist together; this condition arises at what is called the triple point, indicated by point O on the diagram. For water it occurs at 0.0098^{o}C and 0.64 kPa (4.8 mm of mercury) pressure.

If heat is applied to water in any state at constant pressure, the temperature rises and the condition moves horizontally across the diagram, and as it crosses the boundaries a change of state will occur. For example, starting from condition A on the diagram adding heat warms the ice, then melts it, then warms the water and finally evaporates the water to condition A′. Starting from condition B, situated below the triple point, when heat is added, the ice warms and then sublimes without passing through any liquid state.

Liquid and vapour coexist in equilibrium only under the conditions along the line OP. This line is called the vapour pressure/temperature line. The vapour pressure is the measure of the tendency of molecules to escape as a gas from the liquid. The vapour pressure/temperature curve for water is shown in Fig. 7.2, which is just an enlargement for water of the curve OP of Fig. 7.1.

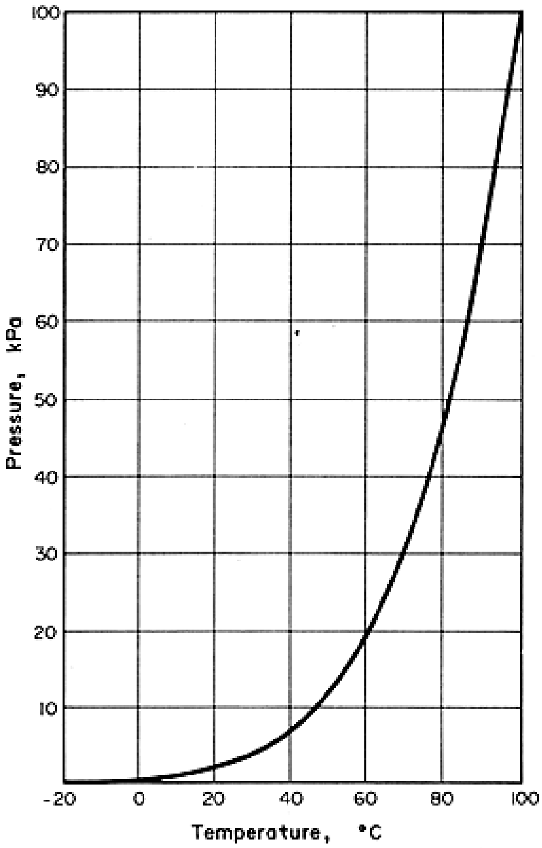

Figure 7.2. Vapour pressure/temperature curve for water

Boiling occurs when the vapour pressure of the water is equal to the total pressure on the water surface. The boiling point at atmospheric pressure is of course 100°C. At pressures above or below atmospheric, water boils at the corresponding temperatures above or below 100°C, as shown in Fig. 7.2 for temperatures below 100°C.

Heat Requirements for Vaporization

The energy, which must be supplied to vaporize the water at any temperature, depends upon this temperature. The quantity of energy required per kg of water is called the **latent heat of vaporization**, if it is from a liquid, or **latent heat of sublimation** if it is from a solid. The heat energy required to vaporize water under any given set of conditions can be calculated from the latent heats given in the steam table in Appendix 8, as steam and water vapour are the same thing.

EXAMPLE 7.1. Heat energy in air drying

A food containing 80% water is to be dried at 100°C down to moisture content of 10%. If the initial temperature of the food is 21°C, calculate the quantity of heat energy required per unit weight of the original material, for drying under atmospheric pressure. The latent heat of vaporization of water at 100°C and at standard atmospheric pressure is 2257kJkg^{-1}. The specific heat capacity of the food is 3.8 kJkg^{-1}°C^{-1} and of water is 4.186 kJkg^{-1}°C^{-1}. Find also the energy requirement/kg water removed.

Calculating for 1 kg food

Initial moisture = 80%

800g moisture are associated with 200 g dry matter.

Final moisture = 10 %,

100g moisture are associated with 900 g dry matter,

Therefore (100 x 200)/900g = 22.2g moisture are associated with 200 g dry matter.

1kg of original matter must lose (800 - 22) g moisture = 778 g = 0.778 kg moisture.

Heat energy required for 1kg original material

= heat energy to raise temperature to 100°C+ latent heat to remove water

= (100 - 21) x 3.8 + 0.778 x 2257

= 300.2 + 1755.9

= <u>2056kJ.</u>

Energy/kg water removed, as 2056 kJ are required to remove 0.778 kg of water,

= 2056/0.778

= <u>2643kJ</u>.

Steam is often used to supply heat to air or to surfaces used for drying. In condensing, steam gives up its latent heat of vaporization; in drying, the substance being dried must take up latent heat of vaporization to convert its liquid into vapour, so it might be reasoned that 1kg of steam condensing will produce 1kg vapour. This is not exactly true, as the steam and the food will in general be under different pressures with the food at the lower pressure. Latent heats of vaporization are slightly higher at lower pressures, as shown in Table 7.1. In practice, there are also heat losses and sensible heat changes that may require to be considered.

TABLE 7.1
LATENT HEAT AND SATURATION TEMPERATURE OF WATER

Absolute Pressure (kPa)	Latent heat of vaporization ($kJkg^{-1}$)	Saturation temperature (^oC)
1	2485	7
2	2460	18
5	2424	33
10	2393	46
20	2358	60
50	2305	81
100	2258	99.6
101.35 (1 atm)	2257	100
110	2251	102
120	2244	105
200	2202	120
500	2109	152

EXAMPLE 7.2. Heat energy in vacuum drying
Using the same material as in Example 7.1, if vacuum drying is to be carried out at 60^{o}C under the corresponding saturation pressure of 20kPa abs. (or a vacuum of 81.4 kPa), calculate the heat energy required to remove the moisture per unit weight of raw material.

Heat energy required per kg raw material
= heat energy to raise temperature to 60^{o}C + latent heat of vaporization at 20 kPa abs.
= (60 - 21) x 3.8 + 0.778 x 2358
= 148.2 + 1834.5
= <u>1983kJ</u>.

In freeze drying the latent heat of sublimation must be supplied. Pressure has little effect on the latent heat of sublimation, which can be taken as 2838 kJ kg^{-1}.

EXAMPLE 7.3. Heat energy in freeze drying
If the food in the two previous examples was to be freeze dried at 0^{o}C, how much energy would be required per kg of raw material, starting from frozen food at 0^{o}C?

Heat energy required per kg raw material
= wt. of water vaporised x latent heat of sublimation
= 0.778 x 2838
= <u>2208kJkg^{-1}</u>.

Heat Transfer in Drying

We have been discussing the heat energy requirements for the drying process. The rates of drying are generally determined by the rates at which heat energy can be transferred to the water or to the ice in order to provide the latent heats, though under some circumstances the rate of mass transfer (removal of the water) can be limiting. All three of the mechanisms by which heat is transferred - conduction, radiation and convection - may enter into drying. The relative importance of the mechanisms varies from one drying process to another and very often one mode of heat transfer predominates to such an extent that it governs the overall process.

As an example, in air drying the rate of heat transfer is given by:

$$q = h_s A(T_a - T_s) \qquad (7.1)$$

where q is the heat transfer rate in Js^{-1}**,** h_s is the surface heat-transfer coefficient $Jm^{-2}s^{-1} {}^oC^{-1}$**,** A is the area through which heat flow is taking place, m^2, T_a is the air temperature and T_s is the temperature of the surface which is drying, ^oC.

To take another example, in a roller dryer where moist material is spread over the surface of a heated drum, heat transfer occurs by conduction from the drum to the foodstuff, so that the equation is

$$q = UA(T_d - T_s)$$

where U is the overall heat-transfer coefficient, T_d is the drum temperature (usually very close to that of the steam), T_s is the surface temperature of the food (boiling point of water or slightly above) and A is the area of drying surface on the drum.

The value of U can be estimated from the conductivity of the drum material and of the layer of foodstuff. Values of U have been quoted as high as 1800 $Jm^{-2}s^{-1} {}^oC^{-1}$ under very good conditions and down to about 60 $Jm^{-2} s^{-1} {}^oC^{-1}$ under poor conditions.

In cases where substantial quantities of heat are transferred by radiation, it should be remembered that the surface temperature of the food may be higher than the air temperature. Estimates of surface temperature can be made using the relationships developed for radiant heat transfer although the actual effect of combined radiation and evaporative cooling is complex. Convection coefficients also can be estimated using the standard equations.

For freeze drying, energy must be transferred to the surface at which sublimation occurs. However, it must be supplied at such a rate as not to increase the temperature at the drying surface above the freezing point. In many applications of freeze drying, the heat transfer occurs mainly by conduction.

As drying proceeds, the character of the heat transfer situation changes. Dry material begins to occupy the surface layers and conduction must take place through these dry surface layers which are poor heat conductors so that heat is transferred to the drying region progressively more slowly.

Dryer Efficiencies

Energy efficiency in drying is of obvious importance as energy consumption is such a large component of drying costs. Basically it is a simple ratio of the minimum energy needed to the energy actually consumed. But because of the complex relationships of the food, the water, and the drying medium which is often air, a number of efficiency measures can be worked out, each appropriate to circumstances and therefore selectable to bring out special features important in the particular process. Efficiency calculations are useful when assessing the performance of a dryer, looking for improvements, and in making comparisons between the various classes of dryers which may be alternatives for a particular drying operation.

Heat has to be supplied to separate the water from the food. The minimum quantity of heat that will remove the required water is that needed to supply the latent heat of evaporation, so one measure of efficiency is the ratio of that minimum to the energy actually provided for the process. Sensible heat can also be added to the minimum, as this added heat in the food often cannot be economically recovered.

Yet another useful measure for air drying such as in spray dryers, is to look at a heat balance over the air, treating the dryer as adiabatic with no exchange of heat with the surroundings. Then the useful heat transferred to the food for its drying corresponds to the drop in temperature in the drying air, and the heat which has to be supplied corresponds to the rise of temperature of the air in the air heater. So this adiabatic air-drying efficiency, η, can be defined by:

$$\eta = (T_1 - T_2)/(T_1 - T_a) \qquad (7.2)$$

where T_1 is the inlet (high) air temperature into the dryer, T_2 is the outlet air temperature from the dryer, and T_a is the ambient air temperature. The numerator, the gap between T_1 and T_2, is a major factor in the efficiency.

EXAMPLE 7.4. Efficiency of a potato dryer

A dryer reduces the moisture content of 100kg of a potato product from 80% to10% moisture. 250kg of steam at 70kPa gauge is used to heat 49,800m^3 of air to 80^{o}C, and the air is cooled to 71^{o}C in passing through the dryer. Calculate the efficiency of the dryer. The specific heat of potato is 3.43kJkg^{-1o}C^{-1}. Assume potato enters at 24^{o}C, which is also the ambient air temperature, and leaves at the same temperature as the exit air.

In 100kg of raw material there is 80% moisture, that is 80kg water and 20kg dry material,

total weight of dry product	= 20 x (10/9)
	= 22.2 kg
weight of water	= (22.2 - 20)
	= 2.2 kg.
water removed	= (80 - 2.2)
	= 77.8 kg.

Heat supplied to potato product

= sensible heat to raise potato product temperature from 24^{o}C to 71^{o}C

+ latent heat of vaporization.

Now, the latent heat of vaporization corresponding to a saturation temperature of 71^{o}C is 2331 kJkg^{-1}

Heat (minimum) supplied/100kg potato	= 100 x (71 - 24) x 3.43 + 77.8 x 2331
	= 16 x 10^3 + 181 x 10^3
	= 1.97 x l0^{5}kJ.
Heat to evaporate water only	= 77.8 x 2331
	= 1.81 x l0^{5}kJ

The specific heat of air is 1.0 Jkg^{-1o}C^{-1} and the density of the air 1.06kgm^{-3} (Appendix 3)

Heat given up by air/100 kg potato = 1.0 x (80 - 71) x 49,800 x 1.06
= 4.75 x 10^5kJ.

The latent heat of steam at 70 kPa gauge(170Pa abs) is 2216 kJkg^{-1}
Heat in steam = 250 x 2216
= 5.54 x 10^5kJ.

Therefore (a) efficiency based on latent heat of vaporisation only:
= (1.81 x 10^5)/ (5.54 x 10^5)
= 33%

(b) efficiency assuming sensible heat remaining in food after drying is unavailable
= (1.97 x 10^5)/ (5.54 x 10^5)
= 36%

(c) efficiency based heat input and output, in drying air (Eqn.7.2)

$\eta = (T_1 - T_2)/(T_1 - T_a)$
= (80 – 71)/ (80 – 24)
= 16%

Whichever of these is chosen depends on the objective for considering efficiency. For example in a spray dryer, the efficiency calculated on the air temperatures shows clearly and emphatically the advantages gained by operating at the highest feasible air inlet temperature and the lowest air outlet temperatures that can be employed in the dryer.

Examples of overall thermal efficiencies are:

drum dryers	35-80%
spray dryers	20-50%
radiant dryers	30-40%

After sufficient energy has been provided to vaporize or to sublime moisture from the food, some way must be found to remove this moisture. In freeze-drying and vacuum systems it is normally convenient to condense the water to a liquid or a solid and then the vacuum pumps have to handle only the non-condensible gases. In atmospheric drying a current of air is normally used.

MASS TRANSFER IN DRYING

In heat transfer, heat energy is transferred under the driving force provided by a temperature difference, and the rate of heat transfer is proportional to the potential (temperature) difference and to the properties of the transfer system characterized by the heat-transfer coefficient. In the same way, mass is transferred under the driving force provided by a partial pressure or concentration difference. The rate of mass transfer is proportional to the potential (pressure or concentration) difference and to the properties of the transfer system characterized by a mass-transfer coefficient.

Writing these symbolically, analogous to $q = UA\,\Delta T$, we have

$$\frac{dw}{dt} = k_g{}' A\,\Delta Y \qquad (7.3)$$

where dw is the mass (moisture) being transferred kgs^{-1}in time dt, A is the area through which the transfer is taking place, k_g' is the mass transfer coefficient in this case in units kgm^{-2}s^{-1} **,** and ΔY is the humidity difference in kgkg^{-1}. Unfortunately the application of mass transfer is not as straightforward as heat transfer. One reason is that the movement pattern of moisture changes as drying proceeds. Initially, the mass (moisture) is transferred from the surface of the material and later, to an increasing extent, from deeper within the food to the surface and thence to the air. So the first stage is to determine the relationships between the moist surface and the ambient air and then to consider the diffusion through the food. In studying the surface/air relationships, it is necessary to consider mass and heat transfer simultaneously.

Air for drying is usually heated and it is also a major heat transfer medium. Therefore it is necessary to look carefully into the relationships between air and the moisture it contains.

PSYCHROMETRY

The capacity of air for moisture removal depends on its humidity and its temperature. The study of relationships between air and its associated water is called psychrometry.

Humidity *(Y)* is the measure of the water content of the air. The absolute humidity is the mass of water vapour per unit mass of dry air and the units are therefore kg kg^{-1}. Absolute humidity is often called just 'humidity', as in this text. It is named absolute humidity or humidity ratio in charts.

Air is said to be saturated with water vapour at a given temperature and pressure if its humidity is a maximum under these conditions. If further water is added to saturated air, it must appear as liquid water in the form of a mist or droplets. Under conditions of saturation, the partial pressure of the water vapour in the air is equal to the saturation vapour pressure of water at that temperature.

The total pressure of a gaseous mixture, such as air and water vapour, is made up from the sum of the pressures of its constituents, which are called the partial pressures. Each partial pressure arises from the molecular concentration of the constituent and the pressure exerted by each gas is that which corresponds to the number of moles present and the total volume of the system. The partial pressures are added to obtain the total pressure.

EXAMPLE 7.5. Partial pressure of water vapour
If the total pressure of moist air is 100kPa (approximately atmospheric) and the humidity is measured as 0.03kg kg^{-1}**,** calculate the partial pressure of the water vapour.

The mole fraction of the water is the number of moles of water to the total number of moles (water + dry air)
The molecular weight of air is 29, and of water 18
So the mole fraction of water = 0.03 /18 (1.00/29   + 0.03/18)
= 0.0017/(0.034 + 0.0017)
= 0.048
Therefore the water vapour pressure = 0.048 x l00kPa
= <u>4.8kPa</u>.

The relative humidity (RH) is defined as the ratio of the partial pressure of the water vapour in the air (p) to the partial pressure of saturated water vapour at the same temperature (p_s). Therefore:

$$RH = p/p_s$$

and is often expressed as a percentage = 100 p/p_s

EXAMPLE 7.6. Relative humidity
If the air in Example 7.5 is at 60°C, calculate the relative humidity.

From steam tables, the saturation pressure of water vapour at 60°C is 19.9 kPa.
Therefore the relative humidity = p/p_s
= 4.8/19.9
= 0.24
or 24%.

If such air were cooled, then when the percentage relative humidity reached 100% the air would be saturated and this would occur at that temperature at which $p = p_s$ = 4.8 kPa.

Interpolating from the steam tables, or reading from the water vapour pressure/temperature graph, this occurs at a temperature of 32°C and this temperature is called the dew-point of the air at this particular moisture content. If cooled below the dew-point, the air can no longer retain this quantity of water as vapour and so water must condense out as droplets or a fog, and the water remaining as vapour in the air will be that corresponding to saturation at the temperature reached.

The humidity Y can therefore be related to the partial pressure p_w of the water in air vapour by the equation:

$$Y = 18\, p_w /[29(P - p_w)] \qquad (7.4)$$

where P is the total pressure. In circumstances where p_w is small compared with P, and this is approximately the case in air/water systems at room temperatures, $Y \approx 18\, p_w / 29P$.

Corresponding to the specific heat capacity, c_p, of gases, is the humid heat, c_s of moist air. It is used in the same way as a specific heat capacity, the enthalpy change being the mass of dry air multiplied by the temperature difference and by the humid heat. The units are $\mathrm{Jkg^{-1}{}^{o}C}$ and the numerical values can be read off a psychrometric chart. It differs from specific heat capacity at constant pressure in that it is based only on the mass of the dry air. The specific heat of the water it contains is effectively incorporated into the humid heat which therefore is numerically a little larger than the specific heat capacity to allow for this.

Wet-bulb Temperatures

A useful concept in psychrometry is the wet-bulb temperature, as compared with the ordinary temperature, which is called the dry-bulb temperature. The wet-bulb temperature is the temperature reached by a water surface, such as that registered by a thermometer bulb surrounded by a wet wick, when exposed to air passing over it. The wick and therefore the thermometer bulb decreases in temperature below the dry-bulb temperature, until the rate of heat transfer from the warmer air to the wick is just equal to the rate of heat transfer needed to provide for the evaporation of water from the wick into the air stream.

Equating these two rates of heat transfer gives

$$h_c A(T_\mathrm{a} - T_\mathrm{s}) = \lambda k_g' A(Y_\mathrm{s} - Y_\mathrm{a})$$

where a and s denote actual and saturation temperatures and humidities; h_c is the heat transfer coefficient and k_g' the mass transfer coefficient from the air to the wick surface; λ is the latent heat of evaporation of water.

Therefore $$h_c / k_g' = \lambda (Y_\mathrm{s} - Y_\mathrm{a}) / (T_\mathrm{a} - T_\mathrm{s})$$

As the relative humidity of the air decreases, so the difference between the wet-bulb and dry-bulb temperatures, called the wet-bulb depression, increases and a line connecting wet-bulb temperature and relative humidity can be plotted on a suitable chart. When the air is saturated, the wet-bulb temperature and the dry-bulb temperature are identical.

Therefore if $(T_\mathrm{a} - T_\mathrm{s})$ is plotted against $(Y_\mathrm{s} - Y_\mathrm{a})$ remembering that the point (T_s, Y_s) must correspond to a dew-point condition, we then have a wet-bulb straight line on a temperature/humidity chart sloping down from the point $(T_\mathrm{s}, Y_\mathrm{s})$ with a slope of:

$$-(\lambda k_g'/h_c)$$

A further important concept is that of the adiabatic saturation condition. This is the situation reached by a stream of water, in contact with the humid air. Both ultimately reach a temperature at which the heat lost by the humid air on cooling is equal to the heat of evaporation of the water leaving the stream of water by evaporation.

Under this condition with no heat exchange to the surroundings, the total enthalpy change ($\mathrm{kJkg^{-1}}$dry air)

$$\begin{aligned} \Delta H &= c_s(T_\mathrm{a} - T_\mathrm{s}) + \lambda(Y_\mathrm{s} - Y_\mathrm{a}) = 0 \\ c_s &= -\lambda(Y_\mathrm{s} - Y_\mathrm{a}) / (T_\mathrm{a} - T_\mathrm{s}) \\ &= -h_c / k_g' \end{aligned}$$

where c_s is the humid heat of the air.

Now it just so happens, for the water/air system at normal working temperatures and pressures that for practical purposes the numerical magnitude of the ratio:

$$\frac{h_c}{c_s k_g'} \text{ (known as the Lewis number)} = 1 \qquad (7.5)$$

This has a useful practical consequence. The wet bulb line and the adiabatic saturation line coincide when the Lewis number = 1.

It is now time to examine the chart we have spoken about. It is called a psychrometric chart.

Psychrometric Charts

In the preceding discussion, we have been considering a chart of humidity against temperature, and such a chart is given in skeleton form on Fig.7.3 and more fully in Appendix 9 (a) Normal temperatures, (b) High temperatures.

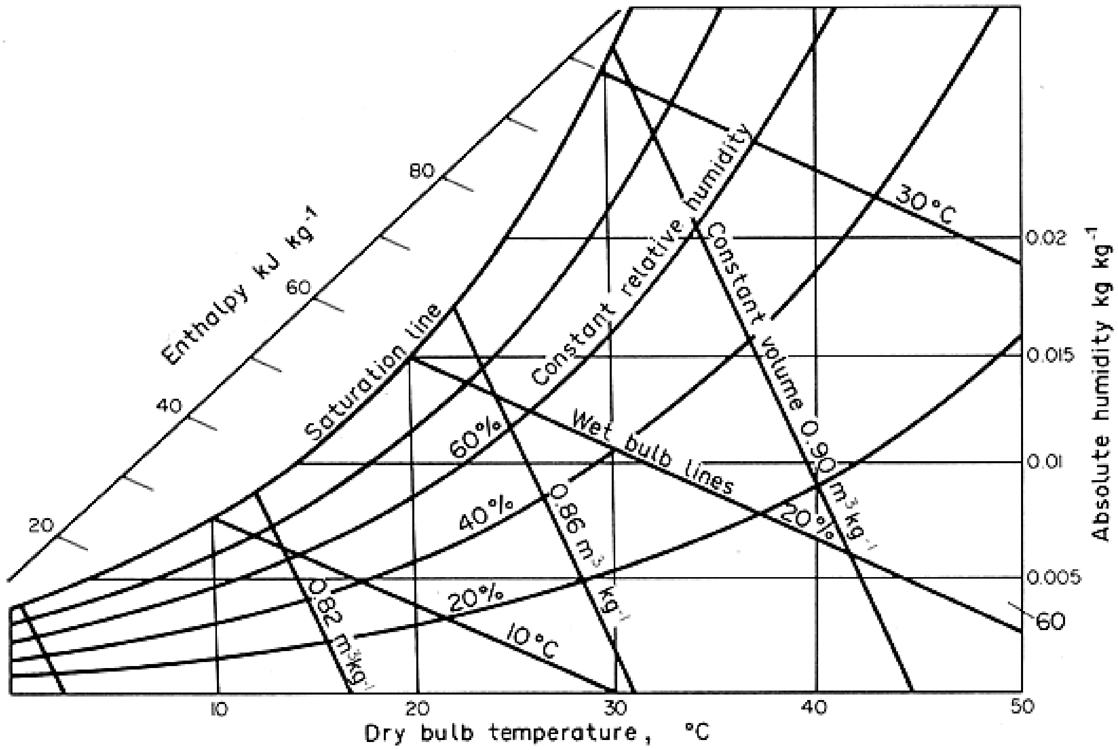

Figure 7.3 Psychrometric chart

The two main axes are temperature (dry bulb) and humidity (absolute). The saturation curve (T_s, Y_s) is plotted on this dividing the whole area into an unsaturated and a two-phase region. Taking a point on the saturation curve (T_s, Y_s) a line can be drawn from this with a slope:

$$- (\lambda\, k_g'/h_c) = (- \lambda/c_s)$$

running down into the unsaturated region of the chart (that “below” the saturation line). This is the wet bulb or adiabatic cooling line and a net of such lines is shown. Any constant temperature line running between the saturation curve and the zero humidity axis can be divided evenly into fractional humidities which will correspond to fractional relative humidities [for example, a 0.50 ratio of humidities will correspond to a 50%RH because of eqn. (7.2) if $P \gg p_w$].

This discussion is somewhat over-simplified and close inspection of the chart shows that the axes are not exactly rectangular and that the lines of constant dry-bulb temperature are not exactly parallel. The reasons are beyond the scope of the present discussion but can be found in appropriate texts such as Keey (1978). The chart also contains other information whose use will emerge as familiarity grows.

This chart can be used as the basis of many calculations. It can be used to calculate relative humidities and other properties.

EXAMPLE 7.7. Relative humidity, enthalpy and specific volume of air
If the wet-bulb temperature in a particular room is measured and found to be 20°C in air whose dry-bulb temperature is 25°C (that is the wet-bulb depression is 5°C) estimate the relative humidity, the enthalpy and the specific volume of the air in the room.

On the humidity chart (Appendix 9a) follow down the wet-bulb line for a temperature of 20°C until it meets the dry-bulb temperature line for 25°C. Examining the location of this point of intersection with reference to the lines of constant relative humidity, it lies between 60% and 70%RH and about 4/10 of the way between them but nearer to the 60% line. Therefore the RH is estimated to be 64%**.** Similar examination of the enthalpy lines gives an estimated enthalpy of 57 kJ kg^{-1}**,** and from the volume lines specific volume of 0.862 $m^3\,kg^{-1}$.

Once the properties of the air have been determined other calculations can easily be made.

EXAMPLE 7.8. Relative humidity of heated air
If the air in Example 7.7 is then to be heated to a dry-bulb temperature of 40°C, calculate the rate of heat supply needed for a flow of 1000$m^3\,h^{-1}$ of this hot air for a dryer, and the relative humidity of the heated air.

On heating, the air condition moves, at constant absolute humidity as no water vapour is added or subtracted, to the condition at the higher (dry bulb) temperature of 40°C. Reading from the chart at 40°C and humidity 0.0125kgkg^{-1}, the enthalpy is 73 kJ kg^{-1}**,** specific volume is 0.906m^3kg^{-1} and RH 27%.

Mass of 1000m^3 is 1000/0.906 = 1104kg,

ΔH = (73 - 57) = 16kJkg^{-1}

So rate of heating required

= 1104 x 16kJh^{-1}

= (1104 x 16)/3600kJs^{-1}

= <u>5kW</u>

If the air is used for drying, with the heat for evaporation being supplied by the hot air passing over a wet solid surface, the system behaves like the adiabatic saturation system. It is adiabatic because no heat is obtained from any source external to the air and the wet solid, and the latent heat of evaporation must be obtained by cooling the hot air. Looked at from the viewpoint of the solid, this is a drying process; from the viewpoint of the air, it is humidification.

EXAMPLE 7.9**.** Water removed in air drying
Air at 60°C and 8%RH is blown through a continuous dryer from which it emerges at a temperature of 35°C. Estimate the quantity of water removed per kg of air passing, and the volume of drying air required to remove 20 kg water per hour.

Using the psychrometric chart (high-temperature version, Appendix 9(b), to take in the conditions), the inlet air condition shows the humidity ratio of the drying air to be 0.01kg kg^{-1} and its specific volume to be 0.96 $m^3\,kg^{-1}$. Through the dryer, the condition of the air follows a constant wet-bulb line at around 27°C, so at 35°C its condition is a humidity ratio of 0.0207.

Water removed $= (0.0207 - 0.010)$
$= \underline{0.0107 kgkg^{-1} \text{ of air}}$.

So each kg, i.e. 0.96 m^3, of air passing will remove 0.0107kg water,

Volume of air to remove 20 kg h^{-1}
$= (20/0.0107) \times 0.96$
$= \underline{1794 m^3 h^{-1}}$

If air is cooled, then initially its condition moves along a line of constant humidity, horizontally on a psychrometric chart, until it reaches the saturation curve at its dew-point. Further cooling then proceeds down the saturation line to the final temperature, with water condensing to adjust the humidity as the saturation humidity cannot be exceeded.

EXAMPLE 7.10. Relative humidity of air leaving a dryer

The air emerging from a dryer, with an exit temperature of 45°C, passes over a surface which is gradually cooled. It is found that the first traces of moisture appear on this surface when it is at 40°C. Estimate the relative humidity of the air leaving the dryer.

On the psychrometric chart, the saturation temperature is 40°C and proceeding at constant humidity from this, the 45°C line is intersected at a point indicating:

relative humidity = 76%

In dryers, it is sometimes useful to reheat the air so as to reduce its relative humidity and thus to give it an additional capacity to evaporate more water from the material being dried. This process can easily be followed on a psychrometric chart.

EXAMPLE 7.11. Reheating of air in a dryer

A flow of 1800$m^3 h^{-1}$ of air initially at a temperature of 18°C and 50% RH is to be used in an air dryer. It is heated to 140°C and passed over a set of trays in a shelf dryer, which it leaves at 60% RH. It is then reheated to 140°C and passed over another set of trays which it leaves at 60% RH again. Estimate the energy necessary to heat the air and the quantity of water removed per hour.

From the psychrometric chart (normal temperatures, Appendix 9(a)), the humidity of the initial air is 0.0062$kgkg^{-1}$**,** specific volume is 0.834$m^3 kg^{-1}$**,** and enthalpy 35$kJkg^{-1}$. Proceeding at constant humidity to a temperature of 140°C, the enthalpy is found (high temperature chart, Appendix 9(b)) to be 160 $kJkg^{-1}$. Proceeding along a wet-bulb line to an RH of 60% gives the corresponding temperature as 48°C and humidity as 0.045 kg kg^{-1}.

Reheating to 140°C keeps humidity constant and enthalpy goes to 268 kJ kg^{-1}.
Thence along a wet-bulb line to 60 % RH gives humidity of 0.082 $kgkg^{-1}$.

Total energy supplied in heating/reheating $= \Delta H$
$= 268 - 35$
$= 233 kJkg^{-1}$

Total water removed $= \Delta Y$
$= 0.082 - 0.0062$
$= 0.0758 kgkg^{-1}$.

1800m^3 of air per hour $= 1800/0.834$

= 2158kgh $^{-1}$
= 0.6kgs $^{-1}$

Energy taken in by air = 233 x 0.6kJs^{-1}
= 140kW

Water removed in dryer = 0.6 x 0.0758
= 0.045kgs^{-1}
= 163kgh $^{-1}$

Exit temperature of air (from chart) = 60^{o}C

Consideration of psychrometric charts, and what has been said about them, will show that they can be used for calculations focused on the air, for the purposes of air conditioning as well as for drying.

EXAMPLE 7.12. Air conditioning
In a tropical country, it is desired to provide processing air conditions of 15^{o}C and 80% RH. The ambient air is at 31.5^{o}C and 90% RH. If the chosen method is to cool the air to condense out enough water to reduce the water content of the air sufficiently, then to reheat if necessary, determine the temperature to which the air should be cooled, the quantity of water removed and the amount of reheating necessary. The processing room has a volume of 1650 m^3 and it is estimated to require six air changes per hour.

Using the psychrometric chart (normal temperatures):
Initial humidity is 0.0266 kg kg^{-1}.
Final humidity is 0.0085 kg kg^{-1}.
Saturation temperature for this humidity is 13^{o}C.
Therefore the air should be cooled to 13^{o}C

At the saturation temperature of 13^{o}C, the enthalpy is 33.5 kJ kg^{-1}
At the final conditions, 15^{o}C and 80 % RH, the enthalpy is 37 kJ kg^{-1}
and the specific volume of air is 0.827 m^3 kg $^{-1}$.

Assuming that the air changes are calculated at the conditions in the working space.

Mass of air to be conditioned = (1650 x 6)/0.827
= 11,970kgh $^{-1}$
Water removed per kg of dry air ΔY
= 0.0266 - 0.0085
= 0.018kgkg^{-1}
Mass of water removed per hour
= 11,970 x 0.018
= 215kgh^{-1}
Reheat required ΔH = (37 - 33.5)
= 3.5kJkg^{-1}
Total reheat power required = 11,970 x 3.5
= 41,895kJh^{-1}
= 11.6kJs^{-1}
= 11.6kW.

Measurement of Humidity

Methods depend largely upon the concepts that have been presented in the preceding sections, but because they are often needed it seems useful to set them out specifically. Instruments for the measurement of humidity are called hygrometers.

- Wet- and dry-bulb thermometers. The dry-bulb temperature is the normal air temperature and the only caution that is needed is that if the thermometer bulb, or element, is exposed to a surface at a substantially higher or lower temperature the possibility of radiation errors should be considered. A simple method to greatly reduce any such error is to interpose a radiation shield, e.g. a metal tube, which stands off from the thermometer bulb 1cm or so and prevents direct exposure to the radiation source or sink. For the wet bulb thermometer, covering the bulb with a piece of wicking, such as a hollow cotton shoelace of the correct size, and dipping the other end of the wick into water so as to moisten the wet bulb by capillary water flow, is adequate. The necessary aspiration of air past this bulb can be effected by a small fan or by swinging bulb, wick, water bottle and all through the air, as in a sling psychrometer. The maximum difference between the two bulbs gives the wet-bulb depression and a psychrometric chart or appropriate tables will then give the relative humidity.

- Dew-point meters. These measure the saturation or dew-point temperature by cooling a sample of air until condensation occurs. The psychrometric chart or a scale on the instrument is then used to give the humidity. For example, a sample of air at 20^{o}C is found to produce the first signs of condensation on a mirror when the mirror is cooled to 14^{o}C. The chart shows by moving horizontally across, from the saturation temperature of 14^{o}C to the constant temperature line at 20^{o}C, that the air must have a relative humidity of 69%.

- The hair hygrometer. Hairs expand and contract in length according to the relative humidity. Instruments are made which give accurately the length of the hair and so they can be calibrated in humidities.

- Electrical resistance hygrometers. Some materials vary in their surface electrical resistance according to the relative humidity of the surrounding air. Examples are aluminium oxide, phenol formaldehyde polymers, and styrene polymers. Calibration allows resistance measurements to be interpreted as humidity.

- Lithium chloride hygrometers. In these a solution of lithium chloride is brought to a temperature such that its partial pressure equals the partial pressure of water vapour in the air. The known vapour pressure/temperature relationships for lithium chloride can then be used to determine the humidity of the air.

EQUILIBRIUM MOISTURE CONTENT

The equilibrium vapour pressure above a food is determined not only by the temperature but also by the water content of the food, by the way in which the water is bound in the food, and by the presence of any constituents soluble in water. Under a given vapour pressure of water in the surrounding air, a food attains a moisture content in equilibrium with its surroundings when there is no exchange of water between the food and its surroundings. This is called its equilibrium moisture content.

It is possible, therefore, to plot the equilibrium vapour pressure against moisture content or to plot the relative humidity of the air in equilibrium with the food against moisture content of the food. Often, instead of the relative humidity, the water activity of the food surface is used. Water activity (a_w) is the ratio of the partial pressure of water in the food to the vapour pressure of water at the same temperature. The equilibrium curves obtained vary with different types of foodstuffs and examples are shown in Fig. 7.4.

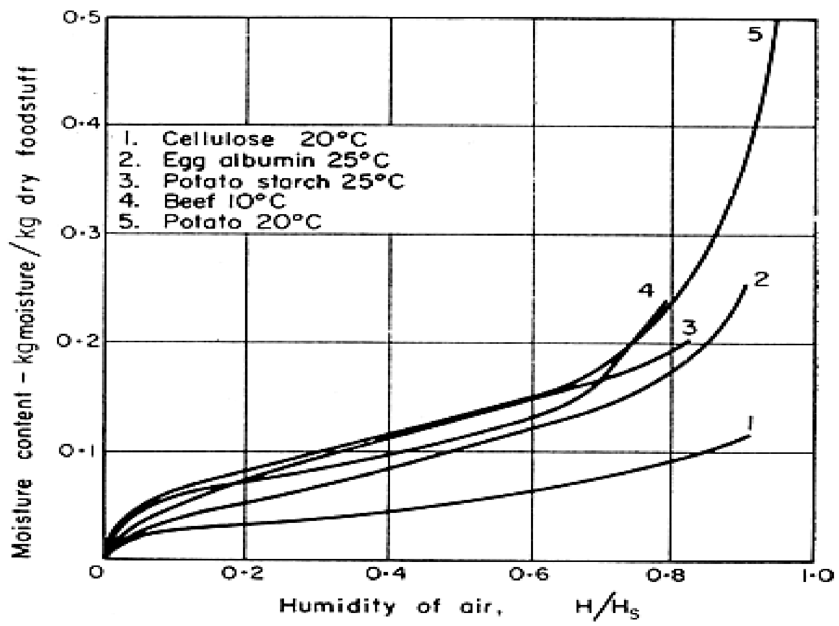

Figure 7.4 Equilibrium moisture contents

Thus, for the potato as shown in Fig. 7.4, at a temperature of 20°C in an atmosphere of relative humidity 30% (giving a water activity of 0.3), the equilibrium moisture content is seen to be 0.1kg water/kg dry potato. It would not be possible to dry potatoes below 10% using an air dryer with air at 20°C and relative humidity 30%. It will be noted from the shape of the curve that above a certain relative humidity, about 80% in the case of potatoes, the equilibrium content increases very rapidly with increase in relative humidity.

There are marked differences between foods, both in shape of the curves and in the amount of water present at any relative humidity and temperature, in the range of relative humidity between 0 and 65%. The sigmoid (S-shaped) character of the curve is most pronounced, and the moisture content at low humidities is greatest, for food whose dry solids are high in protein, starch, or other high molecular weight polymers. The moisture contents at low humidities are low for foods high in soluble solids. Fats and crystalline salts and sugars, in general absorb negligible amounts of water when the RH is low or moderate. Sugars in the amorphous form absorb more than in the crystalline form.

AIR DRYING

In air drying, the rate of removal of water depends on the conditions of the air, the properties of the food and the design of the dryer.

Moisture can be held in varying degrees of bonding. Formerly, it was considered that water in a food came into one or other of two categories, free water or bound water. This now appears to be an oversimplification and such clear demarcations are no longer considered useful. Water is held by forces, whose intensity ranges from the very weak forces retaining surface moisture to very strong chemical bonds. In drying, it is obvious that the water that is loosely held will be removed most easily. Thus it would be expected that drying rates would decrease as moisture content decreases, with the remaining water being bound more and more strongly as its quantity decreases.

In many cases, a substantial part of the water is loosely bound. This water can, for drying purposes, be considered as free water at the surface. A comparison of the drying rates of sand, a material with mostly free water, with meat containing more bound water shows the effect of the binding of water on drying rates. These are shown in Fig. 7.5.

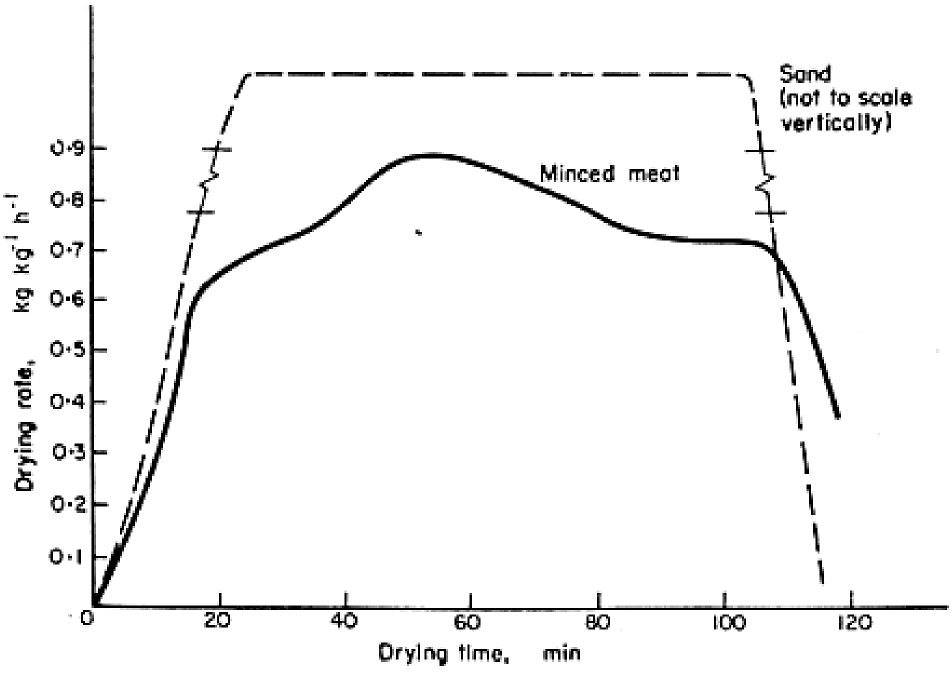

Figure 7.5 Drying rate curves

The behaviour in which the drying behaves as though the water were at a free surface, is called *constant rate drying*. If W is the mass of the material being dried and its moisture content on a dry basis is *X*, then the mass of dry material is:

$$w = \mathrm{W} \times [X/(1+X)]$$

and the mass of associated water is *X*.

Then for constant rate drying:

$$\frac{dwX}{dt} = w\frac{dX}{dt} = \text{constant.}$$

However in food, unlike impervious materials such as sand, after a period of drying at a constant rate it is found that the water then comes off more slowly. A complete drying curve for fish, adapted from Jason (1958), is shown in Fig. 7.6. The drying temperature was low and this accounts for the long drying time.

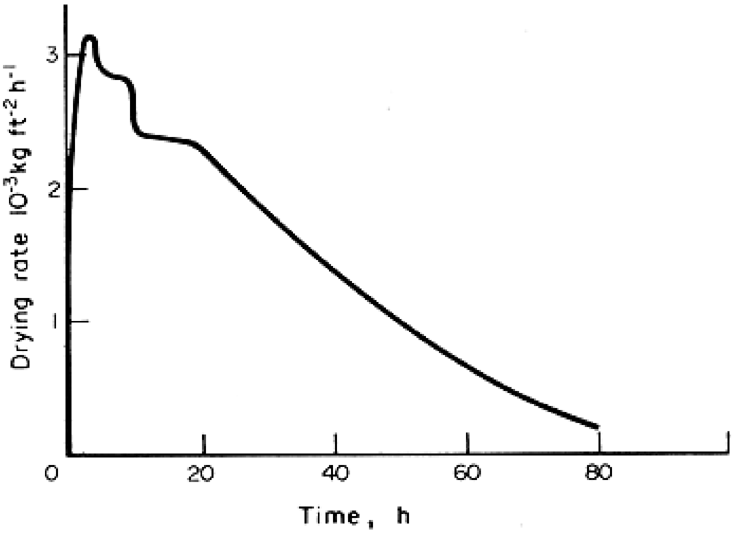

Figure 7.6 Drying curve for fish

A more generalized drying curve plotting the rate of drying as a percentage of the constant rate $(dwX/dt)/(dwX/dt)_{constant}$, against moisture content as ratio of moisture constant to critical moisture (X/X_c), is shown in Fig. 7.7. Note θ is used for time in the Figure.

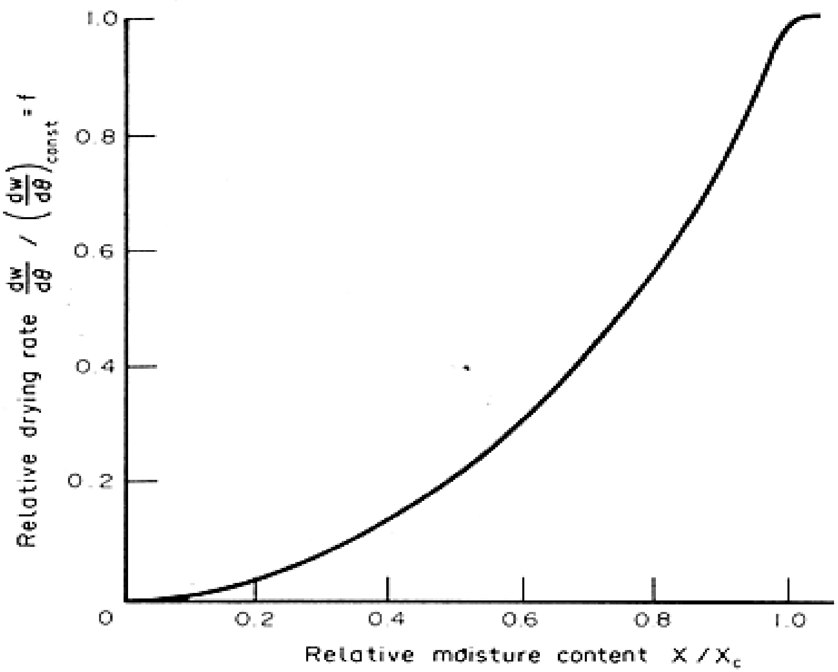

Figure 7.7 Generalised drying curve

The change from constant drying rate to a slower rate occurs at different moisture contents for different foods. However, for many foods the change from constant drying rate occurs at a moisture content in equilibrium with air of 58-65% relative humidity, that is at a_w = 0.58-0.65. The moisture content at which this change of rate occurs is known as the critical moisture content, X_c .

Another point of importance is that many foods such as potato do not show a true constant rate drying period. They do, however, often show quite a sharp break after a slowly and steadily declining drying rate period and the concept of constant rate is still a useful approximation.

The end of the constant-rate period, when $X = X_c$ at the break point of drying rate curves, signifies that the water has ceased to behave as if it were at a free surface and that factors other than vapour pressure differences are influencing the rate of drying. Thereafter the drying rate decreases and this is called the *falling-rate* period of drying. The rate controlling factors in the falling rate period are complex, depending upon diffusion through the food, and upon the changing energy-binding pattern of the water molecules. Very little theoretical information is available for drying of foods in this region and experimental drying curves are the only adequate guide to design.

Calculation of Constant Drying Rates

In the constant rate period, the water is being evaporated from what is effectively a free water surface. The rate of removal of water can then be related to the rate of heat transfer, if there is no change in the temperature of the material and therefore all heat energy transferred to it must result in evaporation of water. The rate of removal of the water is also the rate of mass transfer, from the solid to the ambient air. These two - mass and heat transfer - must predict the same rate of drying for a given set of circumstances.

Considering mass transfer, which is fundamental to drying, the driving force is the difference of the partial water vapour pressure between the food and the air. The extent of this difference can be obtained, knowing the temperatures and the conditions, by reference to tables or the psychrometric chart. Alternatively, the driving force may be expressed in terms of humidity driving forces and the numerical values of the mass transfer coefficients in this case are linked to the others through the partial pressure/humidity relationships such as eqns. (7.4) and (7.5)

EXAMPLE 7.13. Rate of evaporation on drying

The mass transfer coefficient from a free water surface to an adjacent moving air stream has been found to be 0.015 $kgm^{-2}s^{-1}$**.** Estimate the rate of evaporation from a surface of $1m^2$ at a temperature of 28^{o}C into an air stream with a dry-bulb temperature of 40^{o}C and RH of 40% and the consequent necessary rate of supply of heat energy to effect this evaporation.

From charts, the humidity of saturated air at 40^{o}C is $0.0495kgkg^{-1}$.

Humidity of air at 40^{o}C and 40%RH = 0.0495 x 0.4

= $0.0198kgkg^{-1}$

= Y_a

From charts, the humidity of saturated air at 28^{o}C is $0.0244kgkg^{-1}$ = Y_s

Driving force = $(Y_s - Y_a)$
= $(0.0244 - 0.0198)\text{kgkg}^{-1}$
= $0.0046\ \text{kgkg}^{-1}$

Rate of evaporation = $k_g{}'A(Y_s - Y_a)$
= $0.015 \times 1 \times 0.0046$
= $\underline{6.9 \times 10^{-5}\ \text{kgs}^{-1}}$

Latent heat of evaporation of water at 28°C = $2.435 \times 10^3 \text{kJkg}^{-1}$

Heat energy supply rate per square metre = $6.9 \times 10^{-5} \times 2.435 \times 10^3\ \text{kJs}^{-1}$
= $0.168\ \text{kJs}^{-1}$
= $\underline{0.168\ \text{kW}}$.

The problem, in applying such apparently simple relationships to provide the essential rate information for drying, is in the prediction of the mass transfer coefficients. In the section on heat transfer, methods and correlations were given for the prediction of heat transfer coefficients. Such can be applied to the drying situation and the heat transfer rates used to estimate rates of moisture removal. The reverse can also be applied.

EXAMPLE 7.14. Heat transfer in air drying

Using the data from Example 7.13, estimate the heat transfer coefficient needed from the air stream to the water surface.

Heat-flow rate = q = 168 Js^{-1} from Example 7.13.

Temperature difference = dry-bulb temperature of air - wet-bulb temperature (at food surface)
= (40 - 28)
= 12°C = $(T_a - T_s)$

Since $q = h_c A\ (T_a - T_s)$ from Eqn.7.1
$168 = h_c \times 1 \times 12$
$h_c = \underline{14\text{Jm}^{-2}\text{s}^{-1}{}^{\circ}\text{C}^{-1}}$

Mass balances are also applicable, and can be used, in drying and related calculations.

EXAMPLE 7.15. Temperature and RH in air drying of carrots

In a low-temperature drying situation, air at 60°C and 10% RH is being passed over a bed of diced carrots at the rate of 20kg air per second. If the rate of evaporation of water from the carrots, measured by the rate of change of weight of the carrots, is 0.16 kgs^{-1} estimate the temperature and RH of the air leaving the dryer.

From the psychrometric chart

Humidity of air at 60°C and 10%RH
= 0.013kgkg^{-1}.

Humidity added to air from drying carrots
= 0.16 kg/20 kg air
= 0.008kgkg^{-1}

Humidity of air leaving dryer
= 0.013 + 0.008
= $0.021\ \text{kgkg}^{-1}$

Following on the psychrometric chart, the wet-bulb line from the entry point at 60°C and 10%RH up to the intersection of that line with a constant humidity line of 0.021kgkg^{-1}**,** the resulting temperature is 41°C and the RH 42%.

Because the equations for predicting heat transfer coefficients, for situations commonly encountered, are extensive and much more widely available than mass transfer coefficients, the heat transfer rates can be used to estimate drying rates, through the Lewis number. Remember that Le = $(h_c/c_s\, k_g')$ = 1 for the air/water system, from eqn. 7.4.

Strictly speaking the Lewis number, which arises in gaseous diffusion theory, is $(h_c/c_p k_g')$ but for air of the humidity encountered in ordinary practice $c_s \approx c_p \approx$ 1.02 kJkg^{-1}°C^{-1}. Therefore numerically, if h_c is in Jm^{-2}s^{-1}°C^{-1}**,** and k_g' in kgm^{-2}s^{-1}, $k_g' = h_c/1000$, the values of h_c can be predicted using the standard relationships for heat transfer coefficients which have been discussed in Chapter 4.

EXAMPLE 7.16. Lewis relationship in air drying
In Example 7.13 a value for k_g' of 0.0150kgm^{-2}s^{-1} was used. It was also found that the corresponding heat transfer coefficient for this situation was l4 Jm^{-2}s^{-1}°C^{-1}**,** calculated in Example 7.14. Does this agree with the expected value from the Lewis relationship (eqn. 7.4) for the air/water system?

$$h_c = 14 \text{ Jm}^{-2}\text{ s}^{-1}{}^{\circ}\text{C}^{-1}$$
$$\approx 1000 \times 0.0140$$
$$\approx 1000 \times k_g' \text{ as the Lewis relationship predicts.}$$

A convenient way to remember the interrelationship is that the mass transfer coefficient from a free water surface into air expressed in gm^{-2}s^{-1} is numerically approximately equal to the heat transfer coefficient from the air to the surface expressed in Jm^{-2}s^{-1}°C^{-1}.

Falling Rate Drying

The highest rate of drying is normally the constant rate situation, then as drying proceeds the moisture content falls and the access of water from the interior of the food to the surface affects the rate and decreases it. The situation then is complex with moisture gradients controlling the observed drying rates. Actual rates can be measured, showing in the idealized case a constant rate continuing up to the critical moisture content and thereafter a declining rate as the food, on continued drying, approaches the equilibrium moisture content for the food. This is clearly shown by the drying curve of Fig. 7.7 and at low moisture contents the rates of drying become very low. The actual detail of such curves depends, of course, on the specific material and conditions of the drying process.

Calculation of Drying Times

Drying rates, once determined experimentally or predicted from theory, can then be used to calculate drying times so that drying equipment and operations can be designed. In the most general cases, the drying rates vary throughout the dryer with time as drying proceeds, and with the changing moisture content of the material. So the situation is complicated. However, in many cases a simplified approach can provide useful results. One simplification is to assume that the temperature and RH of the drying air are constant.

In this case, for the constant rate period the time needed to remove the quantity of water which will reduce the food material to the critical moisture content X_c (that corresponding to the end of the constant rate period and below which the drying rate falls) can be calculated by dividing this quantity of moisture by the rate.

So $\quad t = w(X_o - X_c)/(dw/dt)_{const.}$ (7.6)

where $\quad (dw/dt)_{const.} = k_g'A(Y_s - Y_a)$

and X_o is the initial moisture content and X_c the final moisture content (the critical moisture content in this case) both on a dry basis, w is the amount of dry material in the food and $(dw/dt)_{const}$ is the constant drying rate. Where the drying rate is reduced by a factor f at various moisture levels, this can be incorporated to give:

$$t = w (X_o - X_f)/ f(w\, dx/dt)_{constant} \quad (7.7)$$
$$= w (X_o - X_f)/f\, k_g'A(Y_s - Y_a)$$

and this has to be integrated piecemeal down to X_f where the subscript f denotes the final water content and f expresses the ratio of the actual drying rate to the maximum drying rate corresponding to the free surface-moisture situation.

EXAMPLE 7.17. Time for air drying at constant rate
100kg of food material are dried from initial water content of 80% on a wet basis and with a surface area of $12m^2$. Estimate the time needed to dry to 50% moisture content on a wet basis, assuming constant rate drying in air at a temperature of 120°C dry bulb and 50°C wet bulb.
Under the conditions in the dryer, measurements indicate the heat transfer coefficient to the food surface from the air to be 18 $Jm^{-2}s^{-1}{}^{o}C^{-1}$.

From the data, calculating moistures on a dry basis:
$X_o = 0.8/(1 - 0.8) = 4kgkg^{-1}$
$X_f = 0.5/(1 - 0.5) = 1kgkg^{-1}$

From the psychrometric chart, $Y_s = 0.087$ and $Y_a = 0.054kgkg^{-1}$

From the Lewis relationship $k_g' = 18gm^{-2}s^{-1} = 0.0l8kgm^{-2}s^{-1}$
$w = 100(1 - 0.8) = 20kg$

Using eqn. (7.6) $\quad t = w(X_o - X_f)/(dw/dt)_{const}$
$= w(X_o - X_f)/ k_g'A(Y_s - Y_a)$
$= 20(4 - 1)/[0.018 \times 12 \times (0.087 - 0.054)]$
$= 60/7.128 \times 10^{-3}$
$= 8417s$
= 2.3 h (to remove 60 kg of water).

During the falling rate period, the procedure outlined above can be extended, using the drying curve for the particular material and the conditions of the dryer. Sufficiently small differential quantities of moisture content to be removed have to be chosen, over which the drying rate is effectively constant, so as to give an accurate value of the total time. As the moisture content above the equilibrium level decreases so the drying rates decrease, and drying times become long.

EXAMPLE 7.18. Time for drying during falling rate
Continuing Example 7.17, for the particular food material, from the 50% moisture content on a wet basis, estimate the total time to dry down to 17% on a wet basis. The drying curve is that illustrated in Fig. 7.7.

Equation (7.7) can be applied, over small intervals of moisture content and multiplying the constant rate by the appropriate reduction factor (f) read of from Fig. 7.7.

$$\Delta t = w\,(\Delta X)/\,f(\mathrm{d}w/\mathrm{d}t)_{\mathrm{const}}$$

$w = 20\mathrm{kg}$ $\qquad (\mathrm{d}w/\mathrm{d}t)_{\mathrm{const}} = 7.128 \times 10^{-3}$

This can be set out in a table. Note the temperature and humidity of the air were assumed to be constant throughout the drying.

Also from equn. 7.7

$$t \quad = w\,(X_o - X_f)/f\,k_g'A(Y_s - Y_a)$$

Moisture content X	1.0	0.8	0.6	0.4	0.3	0.25	0.20	0.18	0.16
$w(X_1 - X_2)$	4	4	4	2	1	1	0.4	0.2	
f (from Fig.7.7)	0.85	0.47	0.24	0.12	0.07	0.05	0.03	0.02	
$f\,k_g'A(Y_s - Y_a) \times 10^{-3}$	6.06	3.35	1.71	0.86	0.50	0.36	0.21	0.14	
t	660	1194	2352	2325	2000	2778	1904	1428	

$$\Sigma\, t = 14641\mathrm{s} = 4.65\mathrm{h}$$

Therefore total drying time = (2.3 + 4.65)h = 6.95h ≈ 7h.

The example shows how as the moisture level descends toward the equilibrium value so the drying rate becomes slower and slower.

In terms of the mass transfer equations, the humidity or partial pressure driving force is tending to zero as the equilibrium moisture content is approached. In terms of the heat transfer equations, the surface temperature rises above the wet-bulb temperature once the surface ceases to behave as a wet surface. The surface temperature then climbs towards the dry-bulb temperature of the air as the moisture 1evel continues to fall, thus leading to a continuously diminishing temperature driving force for surface heat transfer.

This calculation procedure can be applied to more complicated dryers, considering them divided into sections, and applying the drying-rate equations and the input and output conditions to these sections sequentially to build up the whole situation in the dryer.

CONDUCTION DRYING

So far the drying considered has been by hot air. Other methods of drying that are quite commonly encountered are drying by contact with a hot surface; a continuous version of this is the drum or roller dryer where the food is coated as a thin paste over the surface of a slowly revolving heated horizontal cylinder. In such a case, the food dries for as much of one revolution of the cylinder as is mechanically feasible, after which it is scraped off and replaced by fresh wet material. The amount of drying is substantially controlled by the rate of heat transfer and estimates of the heat transfer rate can be used for calculations of the extent of drying.

EXAMPLE 7.19. Moisture content of breakfast food after drum drying
A drum dryer is being used to dry a starch-based breakfast food. The initial moisture content of the food is 75% on a wet basis, the drum surface temperature is 138°C and the food layer outer surface 100°C. The estimated heat transfer coefficient from the drum surface to the drying food is $800 Jm^{-2}s^{-1o}C^{-1}$**.** Assume that the thickness of the food on the drum is 0.3mm and the thermal conductivity of the food is $0.55\ Jm^{-1}s^{-1o}C^{-1}$. If the drum, 1m diameter and 1m in length, is rotating at 2rev/min and the food occupies three-quarters of the circumference, estimate the moisture content of the film being scraped off. Assume the critical moisture content for the food material is 14% on a dry basis, and that conduction heat transfer is through the whole film thickness to give a conservative estimate.

Initial moisture content = 75 % wet basis
= 0.75/(1 -0.75)
= $3 kgkg^{-1}$ dry basis.
Total quantity of material on drum
= $(\pi \times D \times 3/4) \times 1 \times 0.0003 m^3$
= $\pi \times 1 \times 3/4 \times 1 \times 0.0003$
= $7.1 \times 10^{-4} m^3$.
Assuming a density of the food paste of $1000\ kg\ m^3$,
Weight on drum = $7.1 \times 10^{-4} \times 10^3$
= 0.71kg.

Overall resistance to heat transfer, $1/U$ = 1/800 + 0.0003/0.55
= $1.25 \times 10^{-3} + 0.55 \times 10^{-3}$
= 1.8×10^{-3}
Therefore U = $556\ Jm^{-2}s^{-1o}C^{-1}$

$q = UA\,\Delta t$
$= 556 \times 0.75(\pi \times D \times 1) \times (138 - 100)$
$= 4.98 \times 10^4 Js^{-1}$.
$= 49.8\ kJs^{-1}$
Latent heat of evaporation of water = $2257 kJkg^{-1}$
Rate of evaporation = q/λ
= 49.8/2257
= $0.022 kgs^{-1}$.
Residence time of food on drum: at 2 rev min^{-1}
1 revolution takes 30s, but the material is on for 3/4 rev.
Residence time = (3/4) x 30

= 22.5 sec.

Water removed = 22.5 x 0.022

= 0.495 kg.

Initial quantity of water = 0.71 x 0.75

= 0.53 kg

and dry solids = 0.71 x 0.25

= 0.18kg.

Residual water = (0.53-0.495)

= 0.035 kg.

Water content (wet basis) remaining = 0.035/(0.18 + 0.035)

= 16%

DRYING EQUIPMENT

In an industry so diversified and extensive as the food industry, it would be expected that a great number of different types of dryer would be in use. This is the case and the total range of equipment is much too wide to be described in any introductory book such as this. The principles of drying may be applied to any type of dryer, but it should help the understanding of these principles if a few common types of dryers are described.

The major problem in calculations on real dryers is that conditions change as the drying air and the drying solids move along the dryer in a continuous dryer, or change with time in the batch dryer. Such implications take them beyond the scope of the present book, but the principles of mass and heat balances are the basis and the analysis is not difficult once the fundamental principles of drying are understood. Obtaining adequate data may be difficult.

Tray Dryers

In tray dryers, the food is spread out, generally quite thinly, on trays in which the drying takes place. Heating may be by an air current sweeping across the trays, by conduction from heated trays or heated shelves on which the trays lie, or by radiation from heated surfaces. Most tray dryers are heated by air, which also removes the moist vapours.

Tunnel Dryers

These may be regarded as developments of the tray dryer, in which the trays on trolleys move through a tunnel where the heat is applied and the vapours removed. In most cases, air is used in tunnel drying and the material can move through the dryer either parallel or counter current to the air flow. Sometimes the dryers are compartmented, and cross-flow may also be used.

Roller or Drum Dryers

In these the food is spread over the surface of a heated drum. The drum rotates, with the food being applied to the drum at one part of the cycle. The food remains on the drum surface for the greater part of the rotation, during which time the drying takes place, and is then scraped off. Drum drying may be regarded as conduction drying.

Fluidized Bed Dryers

In a fluidized bed dryer, the food material is maintained suspended against gravity in an upward-flowing air stream. There may also be a horizontal air flow helping to convey the food through the dryer. Heat is transferred from the air to the food material, mostly by convection.

Spray Dryers

In a spray dryer, liquid or fine solid material in a slurry is sprayed in the form of a fine droplet dispersion into a current of heated air. Air and solids may move in parallel or counterflow. Drying occurs very rapidly, so that this process is very useful for materials that are damaged by exposure to heat for any appreciable length of time. The dryer body is large so that the particles can settle, as they dry, without touching the walls on which they might otherwise stick. Commercial dryers can be very large, 10m diameter, 20m high.

Pneumatic Dryers

In a pneumatic dryer, the solid food particles are conveyed rapidly in an air stream, the velocity and turbulence of the stream maintaining the particles in suspension. Heated air accomplishes the drying and often some form of classifying device is included in the equipment. In the classifier, the dried material is separated, the dry material passes out as product and the moist remainder is recirculated for further drying.

Rotary Dryers

The foodstuff is contained in a horizontal inclined cylinder through which it travels, being heated either by air flow through the cylinder, or by conduction of heat from the cylinder walls. In some cases, the cylinder rotates and in others the cylinder is stationary and a paddle or screw rotates within the cylinder conveying the material through.

Trough Dryers

The materials to be dried are contained in a trough-shaped conveyor belt, made from mesh, and air is blown through the bed of material. The movement of the conveyor continually turns over the material, exposing fresh surfaces to the hot air.

Bin Dryers

In bin dryers, the foodstuff is contained in a bin with a perforated bottom through which warm air is blown vertically upwards, passing through the material and so drying it.

Belt Dryers

The food is spread as a thin layer on a horizontal mesh or solid belt and air passes through or over the material. In most cases the belt is moving, though in some designs the belt is stationary and the material is transported by scrapers.

Vacuum Dryers

Batch vacuum dryers are substantially the same as tray dryers, except that they operate under a vacuum, and heat transfer is largely by conduction or by radiation. The trays are enclosed in a large cabinet, which is evacuated. The water vapour produced is generally condensed, so that the vacuum pumps have only to deal with non-condensible gases. Another type consists of an evacuated chamber containing a roller dryer.

Freeze Dryers

The material is held on shelves or belts in a chamber that is under high vacuum. In most cases, the food is frozen before being loaded into the dryer. Heat is transferred to the food by conduction or radiation and the vapour is removed by vacuum pump and then condensed. In one process, given the name accelerated freeze drying, heat transfer is by conduction; sheets of expanded metal are inserted between the foodstuffs and heated plates to improve heat transfer to the uneven surface and moisture removal. The pieces of food are shaped so as to present the largest possible flat surface to the expanded metal and the plates to obtain good heat transfer. A refrigerated condenser may be used to condense the water vapour.

Various types of dryers are illustrated in Fig. 7.8.

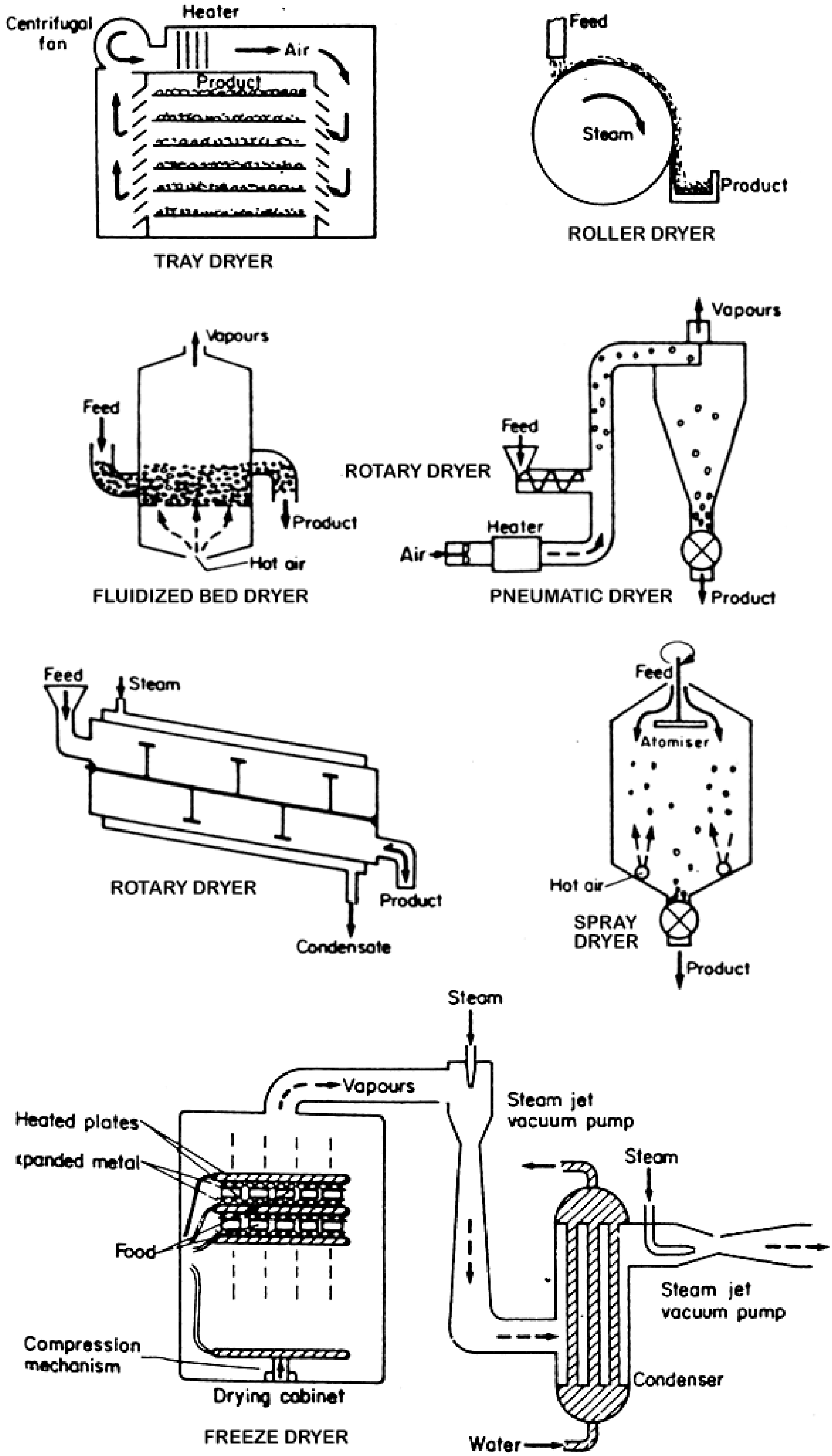

Figure 7.8 Dryers

MOISTURE LOSS IN FREEZERS AND CHILLERS

When a moist surface is cooled by an air flow, and if the air is unsaturated, water will evaporate from the surface to the air. This contributes to the heat transfer, but a more important effect is to decrease the weight of the foodstuff by the amount of the water removed. The loss in weight may have serious economic consequences, since food is most often sold by weight, and also in many foodstuffs the moisture loss may result in a less attractive surface appearance.

To give some idea of the quantities involved, meat on cooling from animal body temperature to air temperature loses about 2% of its weight, on freezing it may lose a further 1% and thereafter if held in a freezer store it loses weight at a rate of about 0.25% per month. After a time, this steady rate of loss in store falls off; but over the course of a year the total store loss may easily be of the order of 2-2.5%. A further consequence is deposition of frost and ice reducing heat transfer on the cooling evaporator surfaces.

To minimize these weight losses, the humidity of the air in freezers, chillers and stores and the rate of chilling and freezing, should be as high as practicable. The design of the evaporator equipment can help if a relatively large coil area has been provided for the freezing or cooling duty. The large area means that the cooling demand can be accomplished with a small air-temperature drop. This may be seen from the standard heat transfer equation:

$$q = UA\,\Delta T$$

For fixed q (determined by the cooling demand) and for fixed U (determined by the design of the freezer) a larger A will mean a smaller ΔT, and vice versa. Since the air leaving the coils will be nearly saturated with water vapour as it leaves, the larger the ΔT the colder the air at this point, and the dryer it becomes. The dryer it becomes (the lower the RH) the greater its capacity for absorbing water from the product. So a low ΔT decreases the drying effect. The water then condenses from the air, freezes to ice on the coils and must be removed, from time to time, by defrosting. Similarly for fixed U and A, a larger q means a larger ΔT, and therefore better insulation leading to a lower q will decrease weight losses.

SUMMARY

1. In drying:
   (a) the latent heat of vaporization must be supplied and heat transferred to do this.
   (b) the moisture must be transported out from the food.

2. Rates of drying depend on:
- vapour pressure of water at the drying temperature,
- vapour pressure of water in the external environment,
- equilibrium vapour pressure of water in the food,
- moisture content of the food.

3. For most foods, drying proceeds initially at a constant rate given by:

$$dw/dt = k_g'A(Y_s - Y_a) = h_cA(T_a - T_s)$$

$$= q/\lambda$$

   for air drying. After a time the rate of drying decreases as the moisture content of the food reaches low values.

4. Air is saturated with water vapour when the partial pressure of water vapour in the air equals the saturation pressure of water vapour at the same temperature.

5. Humidity of air is the ratio of the weight of water vapour to the weight of the dry air in the same volume.

6. Relative humidity is the ratio of the actual to the saturation partial pressure of the water vapour at the air temperature.

7. Water vapour/air humidity relationships are shown on the psychrometric chart.

PROBLEMS

1. Cabbage containing 89%of moisture is to be dried in air at 65°C down to a moisture content on a dry basis of 5%. Calculate (a) the heat energy required per tonne of raw cabbage and (b) per tonne of dried cabbage, for the drying. Ignore the sensible heat and assume the water evaporates at 65°C.
   ((a) 2 x10^6 kJ, (b) 1.73x10^7 kJ)

2. The efficiency of a spray dryer is given by the ratio of the heat energy in the hot air supplied to the dryer and actually used for drying, divided by the heat energy supplied to heat the air from its original ambient temperature. (a) Calculate the efficiency of a spray dryer with an inlet air temperature of 150°C, an outlet temperature of 95°C, operating under an ambient air temperature of 15°C. (b) Suggest how the efficiency of this dryer might be raised.
   ((a) 41%, (b) by either decreasing air outlet temperature or increasing air inlet temperature if the product could tolerate this)

3. Calculate (a) the humidity of air at a temperature of 65°C and in which the RH is 42% and (b) check from a psychrometric chart.

   (0.075 kgkg^{-1})

4. Water at 36°C is to be cooled in an evaporative cooler by air which is at a temperature of 18°C and in which the RH is measured to be 43%. (a) Calculate the minimum temperature to which the water could be cooled. (b) If the water is cooled to 5°C above this temperature, what is the temperature of the chilled water? Check your results on a psychrometric chart.

   ((a) 11°C, (b)16°C)

5. In a chiller store for fruit, which is to be maintained at 5°C, it is important to maintain a daily record of the relative humidity. A wet- and dry-bulb thermometer is available, so prepare a chart giving the relative humidity for the store in terms of the wet-bulb depression.

   (%RH, wet bulb depression [90, 0.7] [80, 1.4] [70, 2.2] [60, 2.9] [50, 3.6][40, 4.4])

6. A steady stream of 1300m^{3}h^{-1} of room air at 16°C and 65%RH is to be heated to 150°C to be used for drying. (a) Calculate the heat input required to accomplish this. If the air leaves the dryer at 90°C and at 5%RH, (b) calculate the quantity of water removed per hour by the dryer, and (c) the quantity of water removed per hour from the material being dried.

   ((a) 58.8kW(b) 37.6kgh^{-1} (c) 27.6kgh^{-1})

7. In a particular situation, the heat transfer coefficient from a food material to air has been measured and found to be 25 Jm^{-2}s^{-1}°C $^{-1}$. If this material is to be dried in air at 90°C and 15%RH, estimate the maximum rate of water removal.

   (1.35kgm^{-2}h^{-1})

8. Food on exposure to unsaturated air at a higher temperature will dry if the air is unsaturated. Steak slices are stored in a chiller at 10°C.
   (a) Estimate the maximum weight loss of steak pieces, 15cm x 5cm x 2cm, in air at 10°C and 50%RH moving at 0.5ms $^{-1}$. The pieces are laid flat on shelves to age. Assuming that the meat behaves as a free water surface, estimate the percentage loss of weight in 1 day of exposure. Specific weight of meat is 1050kgm^{-3}.
   (b) If the RH of the air were increased to 80%, what would be the percentage loss?
   (c) If the meat pieces were also exposed to nearby surfaces at the temperature of the air (dry bulb), what would then be the percentage loss? Assume net emissivity is 0.8.

   ((a) 12% (b) 4.5% (c) 18.4%)

9. Assume that the food material from worked Example 7.17 is to be dried in air at 130°C with a relative humidity of 1.6%. Under these conditions the equilibrium moisture content in the food is 12% on a dry basis. Estimate the time required to dry it from 350% down to 16.3% on a dry basis. Constant rate drying exists down to 100% moisture content on a dry basis. All moisture contents on dry basis.

   (5.8h; 2.03h constant rate, 3.8h falling rate)