# **B. TECH FOOD TECHNOLOGY**

#### 2018-2019

Semester-IV

18BTFT405Unit Operations in Food Processing3H-3C

Instruction Hours/week: L:3 T:0 P:0

Marks: Internal:100 External:-Total:100

# End Semester Exam:3 Hours

## **Course Objectives**

- Discuss the various types of equipments involved in drying and dehydration.
- State the operations involved in mechanical separations.
- Define the various attributes of evaporators in food processing.
- Assess the role of milling equipments in size reduction.
- Outline the agitation and types of impellers employed in mixing.

# **Course Outcomes**

Upon completion of the course, students will be able to:

- 1. Explain the models involved in the moisture and its measurements.
- 2. Investigate the various dryers employed in drying of food.
- 3. Demonstrate the filtration, sedimentation and centrifugal separations.
- 4. Evaluate the heat transfer coefficients and economy of different types of evaporators.
- 5. Estimate the energy and power requirement for the different size reduction operations.
- 6. Design and develop the agitators and impellers for mixing operations.

# **UNIT I - Drying and Dehydration**

Moisture and its measurements - direct and indirect methods – Equilibrium moisture – methods of determination – EMC Models – Henderson, Kelvin, PET and GAB models – importance of EMC- water activity – psychrometry — Drying theory – Drying rate – Mechanical Drying – hot air dryers – Types- fixed -fluidized bed – LSU drier-Spray drier- Osmotic dryer - vacuum shelf dryer – freeze dryer.

# **UNIT II - Mechanical Separation**

Screening: Types, Equipments; Filtration: Filter media types and requirement – constant rate filtration – constant pressure filtration – filter cake resistance – filtration equipments – filter press – rotary drum filters – sedimentation – gravitational sedimentation – Stoke's law – sedimentation in cyclones. Centrifugal separations – rate of separation – centrifuge equipment.

# **UNIT III - Evaporation**

Definition – liquid characteristics – Types of evaporators -single and multiple effect evaporators - once through and circulation evaporators – Agitated film evaporators. Performance

– evaporator capacity – boiling point elevation and Duhring's rule. Heat transfer coefficients –
 Evaporators economy – enthalpy balance of single effect evaporator – multiple effect evaporator
 – methods of feeding. Capacity and economy of multiple effect evaporator.

# **UNIT IV - Size Reduction**

Principles of comminuting – characteristics of comminuted products – particle size distribution in comminuted products – energy and power requirements – Rittinger's, Kick's and Bond's law – Size reduction equipments – crushers – hammer mill – Ball mill-Colloidal mill-attrition mills.

# UNIT V -MIXING AND FORMING

Mixing and forming characteristics of mixtures-measurements of mixing –particles mixing-rates of mixing, energy input in mixing, liquid mixing-power & Froude number-mixing equipment-liquid, powder and particles mixtures, dough and paste mixtures. Forming-Pie & biscuit formers-Bread and confectionery moulders.

# SUGGESTED READINGS

- 1. Rao DG. Fundamentals of Food Engineering. PHI Learning Private Limited, New Delhi, 2009.
- 2. Geankoplis CJ. Transport Processes and Separation Processes Principles. Prentice Hall India, New Delh, 5<sup>th</sup> Edition, 2018.
- 3. Warren, L McCabe, J.C. Smith and Peter Harriot. Unit Operations of Chemical Engineering McGraw Hill International Edition, Singapore, 7<sup>th</sup> Edition, 2004.
- 4. Earle, R.L. Unit Operations in Food Processing". Pergamon Press. UK, 2<sup>nd</sup> Edition, 2003.

# KARPAGAM UNIVERSITY DEPARTMENT OF FOOD TECHNOLOGY B.TECH – FOOD TECHNOLOGY



18BTFT405

UNIT OPERATIONS IN FOOD PROCESSING

# STAFF NAME : Mr.V.Arun Joshy

# CLASS: II Year B.Tech - FOOD TECHNOLOGY; SEMESTER: IV

| S.NO | DESCRIPTION OF PORTIONS TO BE<br>COVERED                                     | HOURS   | Suggetsed<br>Readings used<br>for Teaching | TEACHING<br>AIDS |
|------|--|---------|--|------------------|
|      | UNIT- I DRYING AND DEF   | IYDRATI | ON   |                  |
| 1    | Moisture and its measurements - direct and indirect methods                  | 1       | R [1] pg no107-<br>111                     | BB               |
| 2    | Equilibrium moisture –methods of determination                               | 1       | R [1] pg no 112-<br>113                    | BB               |
| 3    | EMC Models – Henderson, Kelvin, PET and<br>GAB models – importance<br>of EMC | 2       | R [1] pg no 115-<br>117                    | BB               |
| 4    | Water activity   | 1       | W[1]                                       | BB               |
| 5    | Psychrometry — Drying theory – Drying rate                                   | 1       | T[1] pg no 65-<br>78 R[1] pg no<br>125-127 | BB               |

| onit operations   |  |      |   |             |  |
|---|--|------|---|-------------|--|
| 6   | Mechanical Drying – hot air dryers – Types-<br>fixed -fluidized bed – LSU drier-Spray drier-<br>Osmotic dryer - vacuum shelf dryer– freeze<br>dryer. | 2    | T[4] 78   | BB          |  |
| 7   | Tutorial: Important Questions Discussion   | 2    |   |             |  |
|   | TOTAL HOURS FOR UNIT - I   |      | Theory hours:<br>Tutorial hour:<br>Total hours: 1 | 8<br>2<br>0 |  |
|   | UNIT -II MECHANICAL SEPARATION   |      |   |             |  |
| 8   | Screening: Types, Equipments   | 2    | T[3] pg no.<br>1001                               | BB          |  |
| 9   | Filtration: Filter media types and requirement –<br>constant rate filtration – constant pressure<br>filtration – filter cake resistance              | 2    | T[3] pg no.<br>1007-1033                          | BB          |  |
| 10  | filtration equipments – filter press –<br>rotary drum filters  | 1    | T[3] pg no.<br>1033-1037                          | BB          |  |
| 11  | sedimentation – gravitational sedimentation –<br>Stoke's law – sedimentation in cyclones   | 1    | T[3] pg no.<br>1055                               | BB          |  |
| 12  | Centrifugal separations – rate of separation – centrifuge equipment.   | 2    | T[3] pg no.<br>1065                               | BB          |  |
| 13  | Tutorial: Discussion   | 2    |   |             |  |
| TOTAL HOURS FOR UNIT - IITheory hours: 8Total hour: 2Total hours:10 |  |      | 8<br>2<br>0                                       |             |  |
|   | UNIT-III EVAPORA   | TION |   |             |  |
| 14  | Definition – liquid characteristics  | 1    | T[1] pg no. 243-<br>251                           | BB          |  |

| 15                         | Types of evaporators  | 1 | T[1] pg no. 243-<br>251                           | BB          |
|----------------------------|---|---|---|-------------|
| 16                         | single and multiple effect evaporators - once<br>through and circulation evaporators – Agitated<br>film evaporators | 2 | T[1] pg no. 228-<br>239                           | BB          |
| 17                         | Performance –evaporator capacity  | 1 | T[3] pg no. 492                                   | BB          |
| 18                         | boiling point elevation and Duhring's rule  | 1 | T[1] pg no. 230-<br>231                           | BB          |
| 19                         | Heat transfer coefficients –Evaporators<br>economy  | 1 | T[1] pg no. 233-<br>235                           | BB          |
| 20                         | Enthalpy balance of single effect evaporator – multiple effect evaporator –methods of feeding                       | 1 | T[1] pg no. 239                                   | BB          |
| 21                         | Capacity and economy of multiple effect evaporator.   | 1 | T[1] pg no. 240                                   | BB          |
| 22                         | Tutorial: Discuss the important questions   | 2 |   |             |
| TOTAL HOURS FOR UNIT - III |   |   | Theory hours:<br>Tutorial hour:<br>Total hours: 1 | 9<br>2<br>1 |
| UNIT- IV SIZE REDUCTION    |   |   |   |             |
| 23                         | Principles of comminuting – characteristics of comminuted products  | 2 | T[1] pg no. 478                                   | BB          |
| 24                         | particle size distribution in comminuted products   | 1 | T[1] pg no. 478-<br>479                           | BB          |
| 25                         | Energy and power requirements   | 2 | T[1] pg no. 493<br>- 495                          | BB          |

Unit Operations

| 26  | Rittinger's, Kick's and Bond's law   | 1  | T[1] pg no. 479-<br>480 | BB |
|---|--|--|-------------------------|----|
| 27  | Size reduction equipments – crushers – hammer<br>mill – Ball mill-Colloidal mill-attrition<br>mills. | 2  | T[1] pg no. 482-<br>484 | BB |
| 28  | Tutorial: Disscuss and revise the topics; Tests<br>on importance questions                           | 2  |                         |    |
|   | TOTAL HOURS FOR UNIT-IV  | Theory hours: 8<br>Tutorial hour: 2<br>Total hours: 10 |                         |    |
|   | UNIT-V MIXING AND F  | ORMING   | Y<br>J                  |    |
| 29  | Mixing and forming characteristics of mixtures<br>Bread and confectionery moulders.                  | 1  | T[1] pg no. 455-<br>457 | BB |
| 30  | Measurements of mixing –particles mixing rates<br>of mixing, energy input in mixing                  | 2  | T[2] pg no. 450-<br>451 | BB |
| 31  | Liquid mixing-power & Froude number  | 1  | T[1] pg no. 457-<br>460 | BB |
| 32  | Mixing equipment liquid, powder and particles mixtures, dough and paste mixtures                     | 2  | T[1] pg no.460-<br>461  | BB |
| 33  | Forming-Pie & biscuit formers  | 1  | T[1] pg no. 462-<br>463 | BB |
| 34  | Bread and confectionery moulders   | 1  | T[1] pg no. 463-<br>465 | BB |
| 35  | Tutorial: Discuss the questions for thought and review   | 2  |                         |    |
| Theory hours: 8<br>TOTAL HOURS FOR UNIT-V<br>Total hour: 2<br>Total hours: 10 |  | 8<br>2<br>0  |                         |    |
|   | TOTAL HOURS  |  | 51                      |    |

# TEXT BOOKS

| 1 | Rao, D.G. (2009). Fundamentals of Food Engineering. PHI Learning Private Limited,<br>New Delhi.           |
|---|---|
| 2 | Geankoplis C.J Transport Process And Unit Operations, Prentice Hall India, 2002                           |
| 3 | McCabe W.L., Smith J.C, and Harriot P., Unit Operations In Chemical Engineering,<br>McGraw-Hill Inc, 1993 |
| 4 | Earle, R.L. (2003).Unit Operations in Food Processing. 2nd Edition. Pergamon Press. UK                    |

# **Reference Book**

1 K M Sahay (2016).Unit Operations of Agricultural processing.Vikas Publishing House Pvt Ltd.

WEBSITE

1 https://nptel.ac.in/content/storage2/nptel\_data3/html/mhrd/ict/text/126105015/lec21.pdf

# 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.

#### BASIC DRYING THEORY

#### **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°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<sup>-1</sup>. The specific heat capacity of the food is 3.8 kJkg<sup>-1</sup>°C<sup>-1</sup> and of water is 4.186 kJkg<sup>-1</sup>°C<sup>-1</sup>. 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  $100^{\circ}$ 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 = 2643kJ.

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 7.1LATENT HEAT AND SATURATION TEMPERATURE OF WATER

| Absolute       | Latent heat of        | Saturation  |
|----------------|-----------------------|-------------|
| Pressure       | vaporization          | temperature |
| (kPa)          | (kJkg <sup>-1</sup> ) | (°C)        |
| 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°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  $60^{\circ}$ C + latent heat of vaporization at 20 kPa abs.

 $= (60 - 21) \times 3.8 + 0.778 \times 2358$ = 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  $2838 \text{ kJ kg}^{-1}$ .

EXAMPLE 7.3. Heat energy in freeze drying

If the food in the two previous examples was to be freeze dried at 0°C, how much energy would be required per kg of raw material, starting from frozen food at 0°C?

Heat energy required per kg raw material

= wt. of water vaporised x latent heat of sublimation

= 0.778 x 2838

$$=$$
 2208kJkg<sup>-1</sup>.

# 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:

$$q = h_s A(T_a - T_s) \tag{7.1}$$

where q is the heat transfer rate in  $Js^{-1}$ ,  $h_s$  is the surface heat-transfer coefficient  $Jm^{-2}s^{-10}C^{-1}$ , 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, °C.

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

$$q = UA(T_{\rm d} - T_{\rm s})$$

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  $1800 \text{ Jm}^{-2}\text{s}^{-10}\text{C}^{-1}$  under very good conditions and down to about 60 Jm<sup>-2</sup> s<sup>-1</sup> °C<sup>-1</sup> 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,  $\eta$ , can be defined by:

$$\eta = (T_1 - T_2)/(T_1 - T_a) \tag{7.2}$$

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<sup>3</sup> of air to 80°C, and the air is cooled to 71°C in passing through the dryer. Calculate the efficiency of the dryer. The specific heat of potato is 3.43kJkg<sup>-1o</sup>C<sup>-1</sup>. Assume potato enters at 24°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  $24^{\circ}$ C to  $71^{\circ}$ C

+ latent heat of vaporization.

Now, the latent heat of vaporization corresponding to a saturation temperature of  $71^{\circ}$ C is 2331 kJkg<sup>-1</sup>

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

The specific heat of air is  $1.0 \text{ Jkg}^{-10}\text{C}^{-1}$  and the density of the air  $1.06 \text{ kgm}^{-3}$  (Appendix 3)

| Heat given up by air/100 kg potato                                  | = $1.0 \times (80 - 71) \times 49,800 \times 1.06$<br>= $4.75 \times 10^{5}$ kJ. |  |  |
|---|--|--|--|
| The latent heat of steam at 70 kPa gauge(170Pa                      | abs) is 2216 kJkg <sup>-1</sup>  |  |  |
| Heat in steam   | $= 250 \times 2216$  |  |  |
|   | $= 5.54 \text{ x } 10^5 \text{kJ}.$  |  |  |
| Therefore (a) efficiency based on latent heat of vaporisation only: |  |  |  |
|   | $= (1.81 \times 10^5) / (5.54 \times 10^5)$                                      |  |  |
|   | = 33%  |  |  |
| (b) efficiency assuming sensible heat                               | remaining in food after drying is unavailable                                    |  |  |
|   | $= (1.97 \times 10^5) / (5.54 \times 10^5)$                                      |  |  |
|   | = 36%  |  |  |
| (c) efficiency based heat input and our                             | tput, in drying air (Eqn.7.2)  |  |  |
| η   | $= (T_1 - T_2)/(T_1 - T_a)$  |  |  |
|   | = (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

$$\frac{dw}{dt} = k_g \,' A \,\,\Delta Y \tag{7.3}$$

where dw is the mass (moisture) being transferred kgs<sup>-1</sup>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<sup>-2</sup>s<sup>-1</sup>, and  $\Delta Y$  is the humidity difference in kgkg<sup>-1</sup>. 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<sup>-1</sup>. 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<sup>-1</sup>, 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)= 0.048Therefore the water vapour pressure =  $0.048 \times 100$ kPa = 4.8kPa. 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:

$$\mathbf{RH} = p/p_s$$

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 <u>or 24%</u>.

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:

$$Y = 18 p_w / [29(P - p_w)]$$
(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 Jkg<sup>-1o</sup>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

$$h_c A(T_a - T_s) = \lambda k_g A(Y_s - Y_a)$$

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;  $\lambda$  is the latent heat of evaporation of water.

Therefore 
$$h_c / k_g' = \lambda (Y_s - Y_a) / (T_a - T_s)$$

As the relative humidity of the air decreases, so the difference between the wet-bulb and drybulb 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  $(T_a - T_s)$  is plotted against  $(Y_s - Y_a)$  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  $(T_s, Y_s)$  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 (kJkg<sup>-1</sup>dry air)

$$\Delta H = c_s(T_a - T_s) + \lambda(Y_s - Y_a) = 0$$
  

$$c_s = -\lambda(Y_s - Y_a)/(T_a - T_s)$$
  

$$= -h_c /k_g'$$

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:

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

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  $20^{\circ}$ C in air whose dry-bulb temperature is  $25^{\circ}$ C (that is the wet-bulb depression is  $5^{\circ}$ 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<sup>-1</sup>, and from the volume lines specific volume of 0.862 m<sup>3</sup> kg<sup>-1</sup>.

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  $40^{\circ}$ C, calculate the rate of heat supply needed for a flow of  $1000m^3 h^{-1}$  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<sup>-1</sup>, the enthalpy is 73 kJ kg<sup>-1</sup>, specific volume is 0.906m<sup>3</sup>kg<sup>-1</sup> and RH 27%.

Mass of 1000m<sup>3</sup> is 1000/0.906 = 1104kg,  $\Delta H = (73 - 57) = 16 \text{kJkg}^{-1}$ So rate of heating required = 1104 x 16kJh <sup>-1</sup> = (1104 x 16)/3600kJs <sup>-1</sup> = <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  $0.01 \text{kg} \text{ kg}^{-1}$  and its specific volume to be  $0.96 \text{ m}^3 \text{ kg}^{-1}$ . 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)=  $0.0107 \text{kgkg}^{-1}$  of air. So each kg, i.e. 0.96 m<sup>3</sup>, of air passing will remove 0.0107kg water, Volume of air to remove 20 kg h<sup>-1</sup> =  $(20/0.0107) \ge 0.96$ =  $1794 \text{m}^3 \text{h}^{-1}$ 

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  $40^{\circ}$ 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 1800m<sup>3</sup> h<sup>-1</sup> 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 0.0062kgkg<sup>-1</sup>, specific volume is 0.834m<sup>3</sup> kg<sup>-1</sup>, and enthalpy 35kJkg<sup>-1</sup>. Proceeding at constant humidity to a temperature of 140°C, the enthalpy is found (high temperature chart, Appendix 9(b)) to be 160 kJkg<sup>-1</sup>. 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<sup>-1</sup>.

Reheating to 140°C keeps humidity constant and enthalpy goes to 268 kJ kg<sup>-1</sup>. Thence along a wet-bulb line to 60 % RH gives humidity of 0.082 kgkg<sup>-1</sup>.

| Total energy supplied in heating/reheating | $= \Delta H$<br>= 268 - 35<br>= 233kJkg <sup>-1</sup> |
|--|---|
| Total water removed                        | $= \Delta Y = 0.082 - 0.0062 = 0.0758 kg kg^{-1}.$    |
| 1800m <sup>3</sup> of air per hour         | = 1800/0.834  |

|                           | = 2158kgh <sup>-1</sup><br>= 0.6kgs <sup>-1</sup>                                   |
|---------------------------|---|
| Energy taken in by air    | $= 233 \times 0.6 \text{kJs}^{-1}$ $= 140 \text{kW}$                                |
| Water removed in drye     | $r = 0.6 \times 0.0758$<br>= 0.045kgs <sup>-1</sup><br>= <u>163kgh<sup>-1</sup></u> |
| Exit temperature of air ( | from chart) = $60^{\circ}$ 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  $15^{\circ}$ C and 80% RH. The ambient air is at  $31.5^{\circ}$ 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<sup>3</sup> and it is estimated to require six air changes per hour.

Using the psychrometric chart (normal temperatures): Initial humidity is 0.0266 kg kg<sup>-1</sup>. Final humidity is 0.0085 kg kg<sup>-1</sup>. Saturation temperature for this humidity is 13°C. Therefore <u>the air should be cooled to 13°C</u>

At the saturation temperature of 13°C, the enthalpy is 33.5 kJ kg<sup>-1</sup> At the final conditions, 15°C and 80 % RH, the enthalpy is 37 kJ kg<sup>-1</sup> and the specific volume of air is 0.827 m<sup>3</sup> kg<sup>-1</sup>.

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 <sup>-1</sup>    |
| Water removed per kg of dry a | air $\Delta Y$               |
|                               | = 0.0266 - 0.0085            |
|                               | $= 0.018 \text{kgkg}^{-1}$   |
| Mass of water removed per ho  | ur                           |
|                               | = 11,970 x 0.018             |
|                               | = <u>215kgh<sup>-1</sup></u> |
| Reheat required $\Delta H$    | =(37 - 33.5)                 |
|                               | = 3.5kJkg <sup>-1</sup>      |
| Total reheat power required   | = 11,970 x 3.5               |
|                               | = 41,895kJh <sup>-1</sup>    |
|                               | $= 11.6 \text{kJs}^{-1}$     |
|                               | = <u>11.6kW.</u>             |
|                               |                              |

# **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°C is found to produce the first signs of condensation on a mirror when the mirror is cooled to 14°C. The chart shows by moving horizontally across, from the saturation temperature of 14°C to the constant temperature line at 20°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:

 $w = W \ge [X/(1+X)]$ and the mass of associated water is *X*. Then for constant rate drying:

$$\frac{\mathrm{d}wX}{\mathrm{d}t} = w \frac{\mathrm{d}X}{\mathrm{d}t} = \text{constant.}$$

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  $\theta$  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<sup>-2</sup>s<sup>-1</sup>. Estimate the rate of evaporation from a surface of  $1m^2$  at a temperature of 28°C into an air stream with a dry-bulb temperature of 40°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°C is 0.0495kgkg<sup>-1</sup>.

Humidity of air at 40°C and 40%RH =  $0.0495 \times 0.4$ =  $0.0198 \text{kgkg}^{-1}$ =  $Y_a$ 

From charts, the humidity of saturated air at 28°C is 0.0244kgkg<sup>-1</sup> =  $Y_s$ 

| Driving force                               | $= (Y_{s} - Y_{a})$<br>= (0.0244 - 0.0198)kgkg <sup>-1</sup>   |
|---|--|
| Rate of evaporation                         | $= 0.0046 \text{ kgkg}^{-1}$<br>= 0.0046 kgkg^{-1}<br>= k <sub>g</sub> 'A(Y <sub>s</sub> - Y <sub>a</sub> )<br>= 0.015 x 1 x 0.0046<br>= <u>6.9 x 10^{-5} \text{ kgs}^{-1}</u> |
| Latent heat of evaporation of water at 28°C | $= 2.435 \text{ x } 10^3 \text{kJkg}^{-1}$   |
| Heat energy supply rate per square metre    | = $6.9 \times 10^{-5} \times 2.435 \times 10^{3} \text{ kJs}^{-1}$<br>= $0.168 \text{ kJs}^{-1}$<br>= $0.168 \text{ kW}$ .   |

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<sup>-1</sup> from Example 7.13. Temperature difference = dry-bulb temperature of air - wet-bulb temperature (at food surface) = (40 - 28)=  $12^{\circ}C = (T_a - T_s)$ Since  $q = h_c A (T_a - T_s)$  from Eqn.7.1  $168 = h_c x \ 1 x \ 12$  $h_c = 14 Jm^{-2} s^{-10} C^{-1}$ 

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<sup>-1</sup> 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-<sup>1</sup>. Humidity added to air from drying carrots = 0.16 kg/20 kg air = 0.008kgkg<sup>-1</sup> Humidity of air leaving dryer = 0.013 + 0.008= 0.021 kgkg<sup>-1</sup> Following on the psychrometric chart, the wet-bulb line from the entry point at  $60^{\circ}$ C and 10%RH up to the intersection of that line with a constant humidity line of 0.021kgkg<sup>-1</sup>, the resulting temperature is <u>41°C and the RH 42%</u>.

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  $(h_c/c_pk_g')$  but for air of the humidity encountered in ordinary practice  $c_s \approx c_p \approx 1.02$  kJkg<sup>-1o</sup>C <sup>-1</sup>. Therefore numerically, if  $h_c$  is in Jm<sup>-2</sup>s<sup>-1o</sup>C<sup>-1</sup>, and  $k_g'$  in kgm<sup>-2</sup>s<sup>-1</sup>,  $k_g' = h_c/1000$ , 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<sup>-2</sup>s<sup>-1</sup> was used. It was also found that the corresponding heat transfer coefficient for this situation was 14 Jm<sup>-2</sup>s<sup>-1</sup>°C<sup>-1</sup>, calculated in Example 7.14. Does this agree with the expected value from the Lewis relationship (eqn. 7.4) for the air/water system?

$$h_c = 14 \text{ Jm}^{-2} \text{ s}^{-10} \text{C}^{-1}$$
  
\$\approx 1000 x 0.0140  
\$\approx 1000 x k\_g'\$ 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  $\text{gm}^{-2}\text{s}^{-1}$  is numerically approximately equal to the heat transfer coefficient from the air to the surface expressed in  $\text{Jm}^{-2}\text{s}^{-1}\text{C}^{-1}$ .

#### **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 
$$t = w(X_0 - X_c)/(dw/dt)_{const.}$$
 (7.6)  
where  $(dw/dt)_{const.} = k_g' A(Y_s - Y_a)$ 

and  $X_0$  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:

$$t = w (X_0 - X_f) / f(w dx/dt)_{\text{constant}}$$
  
= w (X\_0 - X\_f) / f k\_g' A(Y\_s - Y\_a) (7.7)

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  $120^{\circ}$ C dry bulb and  $50^{\circ}$ C wet bulb.

Under the conditions in the dryer, measurements indicate the heat transfer coefficient to the food surface from the air to be  $18 \text{ Jm}^{-2}\text{s}^{-1}\text{C}^{-1}$ .

From the data, calculating moistures on a dry basis:

$$X_{\rm o} = 0.8/(1 - 0.8) = 4 {\rm kg kg^{-1}}$$
  
 $X_{\rm f} = 0.5/(1 - 0.5) = 1 {\rm kg kg^{-1}}$ 

From the psychrometric chart,  $Y_s = 0.087$  and  $Y_a = 0.054$  kgkg<sup>-1</sup>

From the Lewis relationship  $k_{g}' = 18 \text{gm}^{-2} \text{s}^{-1} = 0.018 \text{kgm}^{-2} \text{s}^{-1}$ w = 100(1 - 0.8) = 20 kg

| Using eqn. (7.6) | $t = w(X_{\rm o} - X_{\rm f})/({\rm d}w/{\rm d}t)_{\rm const}$ |
|------------------|--|
|                  | $= w(X_{\rm o} - X_{\rm f}) / k_g ' A(Y_{\rm s} - Y_{\rm a})$  |
|                  | $= 20(4 - 1)/[0.018 \times 12 \times (0.087 - 0.054)]$         |
|                  | $= 60/7.128 \text{ x } 10^{-3}$                                |
|                  | = 8417s  |
|                  | = <u>2.3 h (to remove 60 kg of water)</u> .                    |

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.

 $\Delta t = w (\Delta X) / f(dw/dt)_{\text{const}}$ 

w = 20 kg (dw/dt)<sub>const</sub> =7.128 x 10<sup>-3</sup>

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  

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

| Moisture content <i>X</i>                            | 1.0 0        | 0.8 0.6      | <b>5</b> 0.4 | l 0.1        | 3 0.         | .25 0.20     | 0.1          | 8 0.16       |
|--|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| $w(X_1 - X_2)$                                       | 4            | 4            | 4            | 2            | 1            | 1            | 0.4          | 0.2          |
| f (from Fig.7.7)<br>$f k_g A(Y_s - Y_a) \ge 10^{-3}$ | 0.85<br>6.06 | 0.47<br>3.35 | 0.24<br>1.71 | 0.12<br>0.86 | 0.07<br>0.50 | 0.05<br>0.36 | 0.03<br>0.21 | 0.02<br>0.14 |
| t  | 660          | 1194         | 2352         | 2325         | 2000         | 2778         | 1904         | 1428         |

 $\Sigma t = 14641s = 4.65h$ 

Therefore total drying time =  $(2.3 + 4.65)h = 6.95h \approx 7h$ .

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 level 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  $800 \text{Jm}^{-2}\text{s}^{-1}\text{C}^{-1}$ . Assume that the thickness of the food on the drum is 0.3mm and the thermal conductivity of the food is  $0.55 \text{ Jm}^{-1}\text{s}^{-1}\text{C}^{-1}$ . 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 that transfer is through the whole film thickness to give a conservative estimate.

| Initial m                  | oisture content                    | =75 % wet basis   |
|----------------------------|------------------------------------|---|
|                            |                                    | = 0.75/(1 - 0.75)   |
|                            |                                    | $= 3 \text{kgkg}^{-1} \text{dry basis.}$                        |
| Total qu                   | antity of mater                    | ial on drum   |
| 1                          | 2                                  | $= (\pi \times D \times 3/4) \times 1 \times 0.0003 \text{m}^3$ |
|                            |                                    | $=\pi \times 1 \times 3/4 \times 1 \times 0.0003$               |
|                            |                                    | $= 7.1 \times 10^{-4} \mathrm{m}^3.$                            |
| Assumir                    | ng a density of                    | the food paste of $1000 \text{ kg m}^3$ .                       |
| Weigh                      | t on drum                          | $= 7.1 \times 10^{-4} \times 10^{3}$                            |
| U                          |                                    | = 0.71kg.   |
|                            |                                    | 6   |
| Overall resistance to hea  | t transfer, $1/U$                  | = 1/800 + 0.0003/0.55   |
|                            |                                    | $= 1.25 \text{ x } 10^{-3} + 0.55 \text{ x } 10^{-3}$           |
|                            |                                    | $= 1.8 \times 10^{-3}$  |
| Therefor                   | re U                               | $= 556 \text{ Jm}^{-2} \text{s}^{-10} \text{C}^{-1}$            |
|                            |                                    |   |
| q                          | $= UA \Delta t$                    |   |
|                            | $= 556 \ge 0.75($                  | π x D x 1) x (138 - 100)  |
|                            | $= 4.98 \text{ x } 10^4 \text{Js}$ | - <sup>1</sup> .  |
|                            | $= 49.8 \text{ kJs}^{-1}$          |   |
| Latent heat of evaporation | on of water $= 2$                  | $257 \mathrm{kJkg}^{-1}$  |
| Rate of evaporation        | $q = q/\lambda$                    |   |
|                            | = 49.8/2257                        |   |
|                            | $= 0.022 \text{kgs}^{-1}$ .        |   |
| Residence time of food     | on drum: at 2 r                    | ev min <sup>-1</sup>  |
| 1 revolution takes 30s     | s, but the mater                   | ial is on for 3/4 rev.  |
| Residence time             | = (3/4) x 30                       |   |
|                            |                                    |   |

|                         | = 22.5 | sec.                 |
|-------------------------|--------|----------------------|
| Water removed           | = 22.5 | x 0.022              |
|                         | = 0.49 | 5 kg.                |
| Initial quantity of wat | er     | $= 0.71 \ge 0.75$    |
|                         |        | = 0.53 kg            |
| and dry s               | solids | $= 0.71 \times 0.25$ |
|                         |        | = 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  $\Delta T$ , and vice versa. Since the air leaving the coils will be nearly saturated with water vapour as it leaves, the larger the  $\Delta T$  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  $\Delta T$  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  $\Delta T$ , 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:

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

$$= q/\lambda$$

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

 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) 
$$2 \times 10^6 \text{ kJ}$$
, (b)  $1.73 \times 10^7 \text{ kJ}$ )

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)

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.

 $(0.075 \text{ kgkg}^{-1})$ 

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<sup>3</sup>h<sup>-1</sup> 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<sup>-1</sup> (c) 27.6kgh<sup>-1</sup>)

- 7. In a particular situation, the heat transfer coefficient from a food material to air has been measured and found to be 25 Jm<sup>-2</sup>s<sup>-1</sup>°C<sup>-1</sup>. If this material is to be dried in air at 90°C and 15%RH, estimate the maximum rate of water removal. (1.35kgm<sup>-2</sup>h<sup>-1</sup>)
- 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<sup>-1</sup>. 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<sup>-3</sup>.
  - (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)

## CHAPTER 10

#### **MECHANICAL SEPARATIONS**

Mechanical separations can be divided into four groups - sedimentation, centrifugal separation, filtration and sieving.

In sedimentation, two immiscible liquids, or a liquid and a solid, differing in density, are separated by allowing them to come to equilibrium under the action of gravity, the heavier material falling with respect to the lighter. This may be a slow process. It is often speeded up by applying centrifugal forces to increase the rate of sedimentation; this is called centrifugal separation. Filtration is the separation of solids from liquids, by causing the mixture to flow through fine pores which are small enough to stop the solid particles but large enough to allow the liquid to pass. Sieving, that is interposing a barrier through which the larger elements cannot pass, is often used for classification of solid particles.

Mechanical separation of particles from a fluid uses forces acting on these particles. The forces can be direct restraining forces such as in sieving and filtration, or indirect as in impingement filters. They can come from gravitational or centrifugal action, which can be thought of as negative restraining forces, moving the particles relative to the containing fluid. So the separating action depends on the character of the particle being separated and the forces on the particle which cause the separation. The important characteristics of the particles are size, shape and density; and of the fluid are viscosity and density. The reactions of the different components to the forces set up relative motion between the fluid and the particles, and between particles of different character. Under these relative motions, particles and fluids accumulate in different regions and can be gathered as in:

- the filter cake and the filtrate tank in the filter press;
- the discharge valve in the base of the cyclone and the air outlet at the top;
- the outlet streams of a centrifuge;
- on the various sized sieves of a sieve set.

In the mechanical separations studied, the forces considered are gravity, combinations of gravity with other forces, centrifugal forces, pressure forces in which the fluid is forced away from the particles, and finally total restraint of solid particles where normally the fluid is of little consequence. The velocities of particles moving in a fluid are important for several of these separations.

# THE VELOCITY OF PARTICLES MOVING IN A FLUID

Under a constant force, for example the force of gravity, particles in a liquid accelerate for a time and thereafter move at a uniform velocity. This maximum velocity which they reach is called their terminal velocity. The terminal velocity depends upon the size, density and shape of the particles, and upon the properties of the fluid.

When a particle moves steadily through a fluid, there are two principal forces acting upon it, the external force causing the motion and the drag force resisting motion which arises from frictional action of the fluid. The net external force on the moving particle is applied force

less the reaction force exerted on the particle by the surrounding fluid, which is also subject to the applied force, so that

$$F_{\rm s} = Va \left( \rho_{\rm p} - \rho_{\rm f} \right)$$

where  $F_s$  is the net external accelerating force on the particle, V is the volume of the particle, a is the acceleration which results from the external force,  $\rho_p$  is the density of the particle and  $\rho_f$  is the density of the fluid.

The drag force on the particle  $(F_d)$  is obtained by multiplying the velocity pressure of the flowing fluid by the projected area of the particle

$$F_{\rm d} = C \rho_{\rm f} v^2 A/2$$

where *C* is the coefficient known as the *drag coefficient*,  $\rho_f$  *is* the density of the fluid, *v* is the velocity of the particle and *A* the projected area of the particle at right angles to the direction of the motion.

If these forces are acting on a spherical particle so that  $V = \pi D^3/6$  and  $A = \pi D^2/4$ , where D is the diameter of the particle, then equating  $F_s$  and  $F_d$ , in which case the velocity v becomes the terminal velocity  $v_m$ , we have:

$$(\pi D^3/6) \ge a (\rho_p - \rho_f) = C \rho_f v_m^2 \pi D^2/8$$

It has been found, theoretically, that for the streamline motion of spheres, the coefficient of drag is given by the relationship:

$$C = 24/(\text{Re}) = 24 \mu / D v_{\text{m}} \rho_{\text{f}}$$

Substituting this value for C and rearranging, we arrive at the equation for the terminal velocity

$$v_{\rm m} = D^2 a(\rho_{\rm p} - \rho_{\rm f}) / 18\mu \tag{10.1}$$

This is the fundamental equation for movement of particles in fluids.

#### SEDIMENTATION

Sedimentation uses gravitational forces to separate particulate material from fluid streams. The particles are usually solid, but they can be small liquid droplets, and the fluid can be either a liquid or a gas. Sedimentation is very often used in the food industry for separating dirt and debris from incoming raw material, crystals from their mother liquor and dust or product particles from air streams.

In sedimentation, particles are falling from rest under the force of gravity. Therefore in sedimentation, eqn. (10.1) takes the familiar form of **Stokes' Law**:

$$v_{\rm m} = D^2 g(\rho_{\rm p} - \rho_{\rm f}) / 18\mu \tag{10.2}$$

Note that eqn. (10.2) is not dimensionless and so consistent units must be employed throughout. For example in the SI system, *D* in m, g in ms<sup>-2</sup>,  $\rho$  in kgm<sup>-3</sup> and  $\mu$  in Nsm<sup>-2</sup>, and then  $\nu_m$  would be in ms<sup>-1</sup>. Particle diameters are usually very small and are often measured in microns (micro-metres) = 10<sup>-6</sup>m with the symbol  $\mu$ m.

Stoke's Law applies only in streamline flow and strictly only to spherical particles. In the case of spheres, the criterion for streamline flow is that (Re)  $\leq 2$ , and many practical cases occur in the region of streamline flow, or at least where streamline flow is a reasonable approximation. Where higher values of the Reynolds number are encountered, more detailed references should be sought, such as Henderson and Perry (1955), Perry (1997) and Coulson and Richardson (1978).

EXAMPLE 10.1. Settling velocity of dust particles

Calculate the settling velocity of dust particles of (a)  $60\mu$ m and (b)  $10\mu$ m diameter in air at 21°C and 100kPa pressure. Assume that the particles are spherical and of density 1280kgm<sup>3</sup>, and that the viscosity of air =  $1.8 \times 10^{-5}$  Ns m<sup>-2</sup> and density of air = 1.2kgm<sup>-3</sup>.

(a) For 60µm particle:

$$v_m = (\underline{60 \times 10^{-6}})^2 \times 9.81 \times (\underline{1280 - 1.2})$$
  
(18 x 1.8 x 10<sup>-5</sup>)  
= 0.14 ms<sup>-1</sup>

(b) For 10 $\mu$ m particles since  $v_m$  is proportional to the squares of the diameters,

$$v_m = 0.14 \text{ x} (10/60)^2$$
$$= 3.9 \text{ x} 10^{-3} \text{ms}^{-1}$$

Checking the Reynolds number for the 60µm particles,

(Re) = 
$$(Dv\rho_f/\mu)$$
  
= (60 x 10<sup>-6</sup> x 0.14 x 1.2) / (1.8 x 10<sup>-5</sup>)  
= 0.56

Stokes' Law applies only to cases in which settling is free, that is where the motion of one particle is unaffected by the motion of other particles.

Where particles are in concentrated suspensions, an appreciable upward motion of the fluid accompanies the motion of particles downward. So the particles interfere with the flow patterns round one another as they fall. Stokes' Law predicts velocities proportional to the square of the particle diameters. In concentrated suspensions, it is found that all particles appear to settle at a uniform velocity once a sufficiently high level of concentration has been reached. Where the size range of the particles is not much greater than 10:1, all the particles tend to settle at the same rate. This rate lies between the rates that would be expected from Stokes' Law for the largest and for the smallest particles. In practical cases, in which Stoke's Law or simple extensions of it cannot be applied, probably the only satisfactory method of obtaining settling rates is by experiment.

## **Gravitational Sedimentation of Particles in a Liquid**

Solids will settle in a liquid whose density is less than their own. At low concentration, Stokes' Law will apply but in many practical instances the concentrations are too high.

In a cylinder in which a uniform suspension is allowed to settle, various quite well defined zones appear as the settling proceeds. At the top is a zone of clear liquid. Below this is a zone of more or less constant composition, constant because of the uniform settling velocity of all sizes of particles. At the bottom of the cylinder is a zone of sediment with the larger particles further down. If the size range of the particles is wide, the zone of constant composition near the top will not occur and an extended zone of variable composition will replace it.

In a continuous thickener, with settling proceeding as the material flows through, and in which clarified liquid is being taken from the top and sludge from the bottom, these same zones occur. The minimum area necessary for a continuous thickener can be calculated by equating the rate of sedimentation in a particular zone to the counter flow velocity of the rising fluid. In this case we have:

$$v_{\rm u} = (F - L)({\rm d}w/{\rm d}t)/A\rho$$

where  $v_u$  is the upward velocity of the flow of the liquid, *F* is the mass ratio of liquid to solid in the feed, *L* is the mass ratio of liquid to solid in the underflow liquid, dw/dt is the mass rate of feed of the solids,  $\rho$  is the density of the liquid and *A* is the settling area in the tank.

If the settling velocity of the particles is *v*, then  $v_u = v$  and, therefore:

$$A = (F - L)(\frac{dw}{dt})/\nu\rho \tag{10.3}$$

The same analysis applies to particles (droplets) of an immiscible liquid as to solid particles. Motion between particles and fluid is relative, and some particles may in fact rise.

## EXAMPLE 10.2. Separating of oil and water

A continuous separating tank is to be designed to follow after a water washing plant for liquid oil. Estimate the necessary area for the tank if the oil, on leaving the washer, is in the form of globules  $5.1 \times 10^{-5}$ m diameter, the feed concentration is 4kg water to 1kg oil, and the leaving water is effectively oil free. The feed rate is 1000kgh<sup>-1</sup>, the density of the oil is 894kgm<sup>-3</sup> and the temperature of the oil and of the water is  $38^{\circ}$ C. Assume Stokes' Law.

| From Appendix 6<br>Viscosity of water<br>Density of water at 38 <sup>0</sup> C | $= 0.7 \text{ x } 10^{-3} \text{Nsm}^{-2}$<br>= 992 kgm <sup>-3</sup>  |
|--|--|
| Diameter of globules   | $= 5.1 \text{ x } 10^{-5} \text{m}$  |
| From eqn. (10.2) $v_{\rm m}$   | $= D^2 g(\rho_p - \rho_f)/18\mu$   |
| $V_{ m m}$   | = $(5.1 \times 10^{-5})^2 \times 9.81 \times (992 - 894)/(18 \times 0.7 \times 10^{-3})$<br>= $1.98 \times 10^{-4} \text{ms}^{-1}$<br>= $0.71 \text{ mh}^{-1}$ |

and since F = 4 and L = 0, and dw/dt =flow of minor component = 1000/5 = 200 kg h<sup>-1</sup>, we have from eqn. (10.3)

$$A = (F - L)(dw/dt)/v\rho$$
  

$$A = 4 \times 200/(0.71 \times 1000)$$
  

$$= 1.1m^{2}$$

**Sedimentation equipment** for separation of solid particles from liquids by gravitational sedimentation is designed to provide sufficient time for the sedimentation to occur and to permit the overflow and the sediment to be removed without disturbing the separation. Continuous flow through the equipment is generally desired, so the flow velocities have to be low enough to avoid disturbing the sediment. Various shaped vessels are used, with a sufficient cross-section to keep the velocities down and fitted with slow speed, scraper conveyors and pumps to remove the settled solids. When vertical cylindrical tanks are used, the scrapers generally rotate about an axis in the centre of the tank and the overflow may be over a weir round the periphery of the tank, as shown diagrammatically in Fig. 10.1.



Figure 10.1 Continuous-sedimentation plant

# Flotation

In some cases, where it is not practicable to settle out fine particles, these can sometimes be floated to the surface by the use of air bubbles. This technique is known as flotation and it depends upon the relative tendency of air and water to adhere to the particle surface. The water at the particle surface must be displaced by air, after which the buoyancy of the air is sufficient to carry both the particle and the air bubble up through the liquid.

Because it depends for its action upon surface forces, and surface forces can be greatly changed by the presence of even minute traces of surface active agents, flotation may be promoted by the use of suitable additives. In some instances, the air bubbles remain round the solid particles and cause froths. These are produced in vessels fitted with mechanical

agitators, the agitators whip up the air/liquid mixture and overflow the froth into collecting troughs.

The greatest application of froth flotation is in the concentration of minerals, but one use in the food industry is in the separation of small particles of fat from water. Dissolving the air in water under pressure provides the froth. On the pressure being suddenly released, the air comes out of solution in the form of fine bubbles which rise and carry the fat with them to surface scrapers.

# Sedimentation of Particles in a Gas

In the food industry, an important application of sedimentation of solid particles occurs in spray dryers. In a spray dryer, the material to be dried is broken up into small droplets of about 100µm diameter and these fall through heated air, drying as they do so. The necessary area for the particles to settle can be calculated in the same way as for sedimentation. Two disadvantages arise from the slow rates of sedimentation: the large chamber areas required and also the long contact times between particles and the heated air which may lead to deterioration of heat sensitive products.

# **Settling Under Combined Forces**

It is sometimes convenient to combine more than one force to effect a mechanical separation. In consequence of the low velocities, especially of very small particles, obtained when gravity is the only external force acting on the system, it is well worthwhile to also employ centrifugal forces. Probably the most common application of this is the cyclone separator. Combined forces are also used in some powder classifiers such as the rotary mechanical classifier and in ring dryers.

# Cyclones

Cyclones are often used for the removal from air streams of particles of about  $10\mu m$  or more in diameter. They are also used for separating particles from liquids and for separating liquid droplets from gases. The cyclone is a settling chamber in the form of a vertical cylinder, so arranged that the particle-laden air spirals round the cylinder to create centrifugal forces which throw the particles to the outside walls. Added to the gravitational forces, the centrifugal action provides reasonably rapid settlement rates. The spiral path, through the cyclone, provides sufficient separation time. A cyclone is illustrated in Fig. 10.2(a).

Stokes' Law shows that the terminal velocity of the particles is related to the force acting. In a centrifugal separator, such as a cyclone, for a particle rotating round the periphery of the cyclone:

$$F_{\rm c} = (mv^2)/r$$
 (10.4)

where  $F_c$  is the centrifugal force acting on the particle, *m* is the mass of the particle, *v* is the tangential velocity of the particle and *r* is the radius of the cyclone.

This equation shows that the force on the particle increases as the radius decreases, for a fixed velocity. Thus, the most efficient cyclones for removing small particles are those of

smallest diameter. The limitations on the smallness of the diameter are both the capital costs of small diameter cyclones to provide sufficient output, and also the pressure drops.



Figure 10.2 Cyclone separator: (a) equipment (b) efficiency of dust collection

The optimum shape for a cyclone has been evolved mainly from experience and proportions similar to those indicated in Fig. 10.2(a), have been found effective. The efficient operation of a cyclone depends very much on a smooth double helical flow being produced and anything which creates a flow disturbance or tends to make the flow depart from this pattern will have considerable and adverse effects upon efficiency. For example, it is important that the air enters tangentially at the top. Constricting baffles or lids should be avoided at the outlet for the air.

The efficiency of collection of dust in a cyclone is illustrated in Fig. 10.2(b). Because of the complex flow, the size cut of particles is not sharp and it can be seen that the percentage of entering particles which are retained in the cyclone falls off for particles below about  $10\mu m$  diameter. Cyclones can be used for separating particles from liquids as well as from gases and also for separating liquid droplets from gases.

#### Impingement separators

Other mechanical flow separators for particles in a gas use the principal of impingement in which deflector plates or rods, normal to the direction of flow, abruptly change the direction of flow. The gas recovers its direction of motion more rapidly than the particles because of its lower inertia. Suitably placed collectors can then be arranged to collect the particles as they are thrown out of the stream. This is the principle of operation of mesh and fibrous air filters. Various adaptations of impingement and settling separators can be adapted to remove particles from gases, but where the particle diameters fall below about 5µm, cloth filters and packed tubular filters are about the only satisfactory equipment.

#### Classifiers

Classification implies the sorting of particulate material into size ranges. Use can be made of the different rates of movement of particles of different sizes and densities suspended in a fluid and differentially affected by imposed forces such as gravity and centrifugal fields, by making suitable arrangements to collect the different fractions as they move to different regions.

Rotary mechanical classifiers, combining differential settling with centrifugal action to augment the force of gravity and to channel the size fractions so that they can be collected, have come into increasing use in flour milling. One result of this is that because of small differences in sizes, shapes and densities between starch and protein-rich material after crushing, the flour can be classified into protein-rich and starch-rich fractions. Rotary mechanical classifiers can be used for other large particle separation in gases.

Classification is also employed in direct air dryers, in which use is made of the density decrease of material on drying. Dry material can be sorted out as a product and wet material returned for further drying. One such dryer uses a scroll casing through which the mixed material is passed, the wet particles pass to the outside of the casing and are recycled while the material in the centre is removed as dry product.

# CENTRIFUGAL SEPARATIONS

The separation by sedimentation of two immiscible liquids, or of a liquid and a solid, depends on the effects of gravity on the components. Sometimes this separation may be very slow because the specific gravities of the components may not be very different, or because of forces holding the components in association, for example as occur in emulsions. Also, under circumstances when sedimentation does occur there may not be a clear demarcation between the components but rather a merging of the layers. For example, if whole milk is allowed to stand, the cream will rise to the top and there is eventually a clean separation between the cream and the skim milk. However, this takes a long time, of the order of one day, and so it is suitable, perhaps, for the farm kitchen but not for the factory. Much greater forces can be obtained by introducing centrifugal action, in a centrifuge. Gravity still acts and the net force is a combination of the centrifugal forces imposed are so much greater than gravity, the effects of gravity can usually be neglected in the analysis of the separation.

The centrifugal force on a particle that is constrained to rotate in a circular path is given by

$$F_{\rm c} = mr\omega^2 \tag{10.5}$$

where  $F_c$  is the centrifugal force acting on the particle to maintain it in the circular path, *r* is the radius of the path, *m* is the mass of the particle, and  $\omega$ (omega) is the angular velocity of the particle.

Or, since  $\omega = v/r$ , where *v* is the tangential velocity of the particle

$$F_{\rm c} = (mv^2)/r$$
 (10.6)

Rotational speeds are normally expressed in revolutions per minute, so that eqn. (10.6) can also be written, as  $\omega = 2\pi N/60$ ; as it has to be in s<sup>-1</sup>, divide by 60.

$$F_c = mr \left(2\pi N/60\right)^2 = 0.011 \ mrN^2 \tag{10.7}$$

where N is the rotational speed in revolutions per minute.

If this is compared with the force of gravity  $(F_g)$  on the particle, which is  $F_g = mg$ , it can be seen that the centrifugal acceleration, equal to  $0.011rN^2$ , has replaced the gravitational acceleration, equal to g. The centrifugal force is often expressed for comparative purposes as so many "g".

EXAMPLE 10.3. Centrifugal force in a centrifuge.

How many "g" can be obtained in a centrifuge which can spin a liquid at 2000 rev/min at a maximum radius of 10cm?

$$F_c = 0.011 \ mrN^2$$
  

$$F_g = mg$$
  

$$F_c/F_g = (0.011rN^2) / g$$
  

$$= (0.011 \ x \ 0.1 \ x \ 2000^2) / 9.81$$
  

$$= \frac{450g}{100}$$

The centrifugal force depends upon the radius and speed of rotation and upon the mass of the particle. If the radius and the speed of rotation are fixed, then the controlling factor is the weight of the particle so that the heavier the particle the greater is the centrifugal force acting on it. Consequently, if two liquids, one of which is twice as dense as the other, are placed in a bowl and the bowl is rotated about a vertical axis at high speed, the centrifugal force per unit volume will be twice as great for the heavier liquid as for the lighter. The heavy liquid will therefore move to occupy the annulus at the periphery of the bowl and it will displace the lighter liquid towards the centre. This is the principle of the centrifugal liquid separator, illustrated diagrammatically in Fig. 10.3.



Figure 10.3 Liquid separation in a centrifuge

#### **Rate of Separation**

The steady-state velocity of particles moving in a streamline flow under the action of an accelerating force is, from eqn. (10.1),

$$v_m = D^2 a (\rho_p - \rho_f) / 18 \mu$$

If a streamline flow occurs in a centrifuge we can write, from eqns. (10.6) and (10.7), as *a* is the tangential acceleration:

$$F_{\rm c} = ma$$
  
$$F_{\rm c}/m = a = r (2\pi N/60)^2$$

so that

$$v_m = D^2 r (2\pi N/60)^2 (\rho_p - \rho_f) / 18\mu$$
  
$$v_m = D^2 N^2 r (\rho_p - \rho_f) / 1640\mu$$
 (10.8)

EXAMPLE 10.4. Centrifugal separation of oil in water

A dispersion of oil in water is to be separated using a centrifuge. Assume that the oil is dispersed in the form of spherical globules  $5.1 \times 10^{-5}$  m diameter; its density is 894 kgm<sup>-3</sup>. If the centrifuge rotates at 1500 rev/mm and the effective radius at which the separation occurs is 3.8cm, calculate the velocity of the oil through the water. Take the density of water to be 1000kgm<sup>-3</sup> and its viscosity to be  $0.7 \times 10^{-3}$ Nsm<sup>-2</sup>. (The separation in this problem is the same as that in Example 10.2, in which the rate of settling under gravity was calculated.)

From eqn. (10.8)

$$v_m = (5.1 \times 10^{-5})^2 \times (1500)^2 \times 0.038 \times (1000 - 894) / (1.64 \times 10^3 \times 0.7 \times 10^{-3})$$
  
=  $0.02 \text{ms}^{-1}$ 

Checking that it is reasonable to assume Stokes' Law

Re = 
$$(Dv\rho/\mu)$$
  
= (5.1 x 10<sup>-5</sup> x 0.02 x 1000)/(0.7 x 10<sup>-3</sup>)  
= 1.5

so that the flow is streamline and it should obey Stokes' Law.

## **Liquid Separation**

The separation of one component of a liquid/liquid mixture, where the liquids are immiscible but finely dispersed, as in an emulsion, is a common operation in the food industry. It is particularly common in the dairy industry in which the emulsion, milk, is separated by a centrifuge into skim milk and cream. It seems worthwhile, on this account, to examine the position of the two phases in the centrifuge as it operates. The milk is fed continuously into the machine, which is generally a bowl rotating about a vertical axis, and cream and skim milk come from the respective discharges. At some point within the bowl there must be a surface of separation between cream and the skim milk.





Consider a thin cylinder, of thickness dr and height b as shown in Fig. 10.4(a): the differential centrifugal force across the thickness dr is given by eqn. 10.5:

$$dF_c = (dm)r\omega^2$$

where  $dF_c$  is the differential force across the cylinder wall, dm is the mass of the differential cylinder,  $\omega$  is the angular velocity of the cylinder and *r* is the radius of the cylinder. But,

$$dm = 2\pi r b \rho dr$$

where  $\rho$  is the density of the liquid and *b* is the height of the cylinder.

Therefore  $dF_c = (2\pi rb\rho dr)r\omega^2$ 

The area over which the force  $dF_c$  acts is  $2\pi rb$ , so that:

$$dP = dF_c / 2\pi rb = \rho \omega^2 r dr$$

where dP is the differential pressure across the wall of the differential cylinder.

To find the differential pressure in a centrifuge, between radius  $r_1$  and  $r_2$ , the equation for d*P* can be integrated, letting the pressure at radius  $r_1$  be  $P_1$  and that at  $r_2$  be  $P_2$ , and so

$$P_2 - P_1 = \rho \omega^2 (r_2^2 - r_1^2)/2 \tag{10.9}$$

Equation (10.9) shows the radial variation in pressure across the centrifuge.

Consider now Fig. 10.4(b), which represents the bowl of a vertical continuous liquid centrifuge. The feed enters the centrifuge near to the axis, the heavier liquid, A, discharges through the top opening 1 and the lighter liquid, B, through the opening 2. Let  $r_1$  be the radius at the discharge pipe for the heavier liquid and  $r_2$  that for the lighter liquid. At some other radius  $r_n$ , there will be a separation between the two phases, the heavier and the lighter. For the system to be in hydrostatic balance, the pressures of each component at radius  $r_n$ , and equating these we have:

$$\rho_{A}\omega^{2} (r_{n}^{2} - r_{1}^{2})/2 = \rho_{B}\omega^{2}(r_{n}^{2} - r_{2}^{2})/2$$

$$\rho_{A}(r_{n}^{2} - r_{1}^{2}) = \rho_{B}(r_{n}^{2} - r_{2}^{2})$$

$$r_{n}^{2} = (\rho_{A}r_{1}^{2} - \rho_{B}r_{2}^{2})/(\rho_{A} - \rho_{B})$$
(10.10)

where  $\rho_A$  is the density of the heavier liquid and  $\rho_B$  is the density of the lighter liquid.

Equation (10.10) shows that as the discharge radius for the heavier liquid is made smaller, then the radius of the neutral zone must also decrease. When the neutral zone is nearer to the central axis, the lighter component is exposed only to a relatively small centrifugal force compared with the heavier liquid. This is applied where, as in the separation of cream from milk, as much cream as possible is to be removed and the neutral radius is therefore kept small. The feed to a centrifuge of this type should be as nearly as possible into the neutral zone so that it will enter with the least disturbance of the system. This relationship can, therefore, be used to place the feed inlet and the product outlets in the centrifuge to get maximum separation.

#### EXAMPLE 10.5. Centrifugal separation of milk and cream

If a cream separator has discharge radii of 5 cm and 7.5 cm and if the density of skim milk is 1032kgm<sup>-3</sup> and that of cream is 915 kgm<sup>-3</sup>, calculate the radius of the neutral zone so that the feed inlet can be designed.

For skim milk,  $r_1 = 0.075$ m,  $\rho_A = 1032$  kgm<sup>-3</sup>; for cream  $r_2 = 0.05$ m,  $\rho_B = 915$  kgm<sup>-3</sup>

From eqn. (10.10)

$$r_n^2 = [1032 \text{ x} (0.075)^2 - 915 \text{ x} (0.05)^2] / (1032 - 915)$$
  
= 0.03m<sup>2</sup>  
$$r_n = 0.17 \text{ m}$$
  
= 17cm

# **Centrifuge Equipment**

The simplest form of centrifuge consists of a bowl spinning about a vertical axis, as shown in Fig. 10.4(a). Liquids, or liquids and solids, are introduced into this and under centrifugal force the heavier liquid or particles pass to the outermost regions of the bowl, whilst the lighter components move towards the centre.

If the feed is all liquid, then suitable collection pipes can be arranged to allow separation of the heavier and the lighter components. Various arrangements are used to accomplish this collection effectively and with a minimum of disturbance to the flow pattern in the machine. To understand the function of these collection arrangements, it is very often helpful to think of the centrifuge action as analogous to gravity settling, with the various weirs and overflows acting in just the same way as in a settling tank even though the centrifugal forces are very much greater than gravity.

In liquid/liquid separation centrifuges, conical plates are arranged as illustrated in Fig. 10.5(a) and these give smoother flow and better separation.



Figure 10.5 Liquid centrifuges: (a) conical bowl, (b) nozzle

Whereas liquid phases can easily be removed from a centrifuge, solids present much more of a problem. In liquid/solid separation, stationary ploughs cannot be used as these create too much disturbance of the flow pattern on which the centrifuge depends for its separation. One method of handling solids is to provide nozzles on the circumference of the centrifuge bowl as illustrated in Fig.10.5(b). These nozzles may be opened at intervals to discharge

accumulated solids together with some of the heavy liquid. Alternatively, the nozzles may be open continuously relying on their size and position to discharge the solids with as little as possible of the heavier liquid. These machines thus separate the feed into three streams, light liquid, heavy liquid and solids, the solids carrying with them some of the heavy liquid as well. Another method of handling solids from continuous feed is to employ telescoping action in the bowl, sections of the bowl moving over one another and conveying the solids that have accumulated towards the outlet, as illustrated in Fig. 10.6(a)



Figure 10.6 Liquid/solid centrifuges(a) telescoping bowl(b) horizontal bowl, scroll discharge

The horizontal bowl centrifuge with scroll discharge, as illustrated in Fig.10.6(b) can discharge continuously. In this machine, the horizontal collection scroll (or screw) rotates inside the conical-ended bowl of the machine and conveys the solids with it, whilst the liquid discharges over an overflow towards the centre of the machine and at the opposite end to the solid discharge. The essential feature of these machines is that the speed of the scroll, relative to the bowl, must not be great. For example, if the bowl speed is 2000rev/min, a suitable speed for the scroll might be 25rev/min relative to the bowl, which would mean a scroll speed of 2025 or 1975rev/min. The differential speeds are maintained by gearing between the driving shafts for the bowl and the scroll. These machines can continuously handle feeds with solid contents of up to 30%. A discussion of the action of centrifuges is given by Trowbridge (1962) and they are also treated in McCabe and Smith (1975) and Coulson and Richardson (1977).

#### FILTRATION

In another class of mechanical separations, placing a screen in the flow through which they cannot pass imposes virtually total restraint on the particles above a given size. The fluid in this case is subject to a force that moves it past the retained particles. This is called filtration. The particles suspended in the fluid, which will not pass through the apertures, are retained

and build up into what is called a filter cake. Sometimes it is the fluid, the filtrate, that is the product, in other cases the filter cake.

The fine apertures necessary for filtration are provided by fabric filter cloths, by meshes and screens of plastics or metals, or by beds of solid particles. In some cases, a thin preliminary coat of cake, or of other fine particles, is put on the cloth prior to the main filtration process. This preliminary coating is put on in order to have sufficiently fine pores on the filter and it is known as a pre-coat.

The analysis of filtration is largely a question of studying the flow system. The fluid passes through the filter medium, which offers resistance to its passage, under the influence of a force which is the pressure differential across the filter. Thus, we can write the familiar equation:

#### rate of filtration = driving force/resistance

Resistance arises from the filter cloth, mesh, or bed, and to this is added the **resistance of the filter cake** as it accumulates. The filter-cake resistance is obtained by multiplying the specific resistance of the filter cake, that is its resistance per unit thickness, by the thickness of the cake. The resistances of the filter material and pre-coat are combined into a single resistance called the filter resistance. It is convenient to express the filter resistance in terms of a fictitious thickness of filter cake. This thickness is multiplied by the specific resistance of the filter resistance. Thus the overall equation giving the **volumetric rate of flow** d V/dt is:

$$\mathrm{d}V/\mathrm{d}t = (A \ \Delta P)/R$$

As the total resistance is proportional to the viscosity of the fluid, we can write:

$$R = \mu r(L_c + L)$$

where *R* is the resistance to flow through the filter,  $\mu$  is the viscosity of the fluid, *r* is the specific resistance of the filter cake,  $L_c$  is the thickness of the filter cake and *L* is the fictitious equivalent thickness of the filter cloth and pre-coat, *A* is the filter area, and  $\Delta P$  is the pressure drop across the filter.

If the rate of flow of the liquid and its solid content are known and assuming that all solids are retained on the filter, the thickness of the filter cake can be expressed by:

$$L_c = wV/A$$

where w is the fractional solid content per unit volume of liquid, V is the volume of fluid that has passed through the filter and A is the area of filter surface on which the cake forms.

The resistance can then be written

$$R = \mu r \left[ w(V/A) + L \right]$$
(10.11)

and the equation for flow through the filter, under the driving force of the pressure drop is then:

$$dV/dt = A \Delta P / \mu r[w(V/A) + L]$$
(10.12)

Equation (10.12) may be regarded as the fundamental equation for filtration. It expresses the rate of filtration in terms of quantities that can be measured, found from tables, or in some cases estimated. It can be used to predict the performance of large-scale filters on the basis of laboratory or pilot scale tests. Two applications of eqn. (10.12) are filtration at a constant flow rate and filtration under constant pressure.

#### **Constant Rate Filtration**

In the early stages of a filtration cycle, it frequently happens that the filter resistance is large relative to the resistance of the filter cake because the cake is thin. Under these circumstances, the resistance offered to the flow is virtually constant and so filtration proceeds at a more or less constant rate. Equation (10.12) can then be integrated to give the quantity of liquid passed through the filter in a given time. The terms on the right-hand side of eqn.(10.12) are constant so that integration is very simple:

$$\int dV/Adt = V/At = \Delta P/[\mu r w(V/A) + L]$$

$$\Delta P = V/At \ge \mu r[(wV/A) + L]$$
(10.13)

or

From eqn. (10.13) the pressure drop required for any desired flow rate can be found. Also, if a series of runs is carried out under different pressures, the results can be used to determine the resistance of the filter cake.

#### **Constant Pressure Filtration**

Once the initial cake has been built up, and this is true of the greater part of many practical filtration operations, flow occurs under a constant-pressure differential. Under these conditions, the term  $\Delta P$  in eqn. (10.12) is constant and so

$$\mu r[w(V/A) + L]dV = A \Delta P dt$$

and integration from V = 0 at t = 0, to V = V at t = t

 $\mu r[w(V^2/2A) + LV] = A \Delta Pt$  and rewriting this

$$tA/V = (\mu r w/2\Delta P) \times (V/A) + \mu r L/\Delta P$$
(10.14)  
$$t/(V/A) = (\mu r w/2\Delta P) \times (V/A) + \mu r L/\Delta P$$

Equation (10.14) is useful because it covers a situation that is frequently found in a practical filtration plant. It can be used to predict the performance of filtration plant on the basis of experimental results. If a test is carried out using constant pressure, collecting and measuring the filtrate at measured time intervals, a **filtration graph** can be plotted of t/(V/A) against (V/A) and from the statement of eqn. (10.14) it can be seen that this graph should be a straight

line. The slope of this line will correspond to  $\mu r w/2\Delta P$ ; the intercept on the t/(V/A) axis will give the value of  $\mu r L/\Delta P$ . Since, in general,  $\mu$ , w,  $\Delta P$  and A are known or can be measured, the values of the slope and intercept on this graph enable L and r to be calculated.

EXAMPLE 10.6. Volume of filtrate from a filter press

A filtration test was carried out, with a particular product slurry, on a laboratory filter press under a constant pressure of 340 kPa and volumes of filtrate were collected as follows:

| Filtrate volume (kg) | 20 | 40 | 60   | 80 |
|----------------------|----|----|------|----|
| Time (min)           | 8  | 26 | 54.5 | 93 |

The area of the laboratory filter was  $0.186 \text{ m}^2$ . In a plant scale filter, it is desired to filter a slurry containing the same material, but at 50% greater concentration than that used for the test, and under a pressure of 270kPa. Estimate the quantity of filtrate that would pass through in 1 hour if the area of the filter is  $9.3\text{m}^2$ .

From the experimental data:

| V(kg)                                       | 20    | 40   | 60    | 80    |
|---|-------|------|-------|-------|
| t(s)  | 480   | 1560 | 3270  | 5580  |
| <i>V/A</i> (l/m <sup>2</sup> )              | 107.5 | 215  | 323   | 430   |
| t/(V/A) (sm <sup>2</sup> kg <sup>-1</sup> ) | 4.47  | 7.26 | 10.12 | 12.98 |

These values of t/(V/A) are plotted against the corresponding values of V/A in Fig. 10.7. From the graph, we find that the slope of the line is 0.0265, and the intercept 1.6.



Figure 10.7 Filtration Graph

Then substituting in eqn. (10.14) we have t/(V/A) = 0.0265(V/A) + 1.6.

To fit the desired conditions for the plant filter, the constants in this equation will have to be modified. If all of the factors in eqn. (10.14) except those which are varied in the problem are combined into constants, *K* and *K'*, we can write

$$t/(V/A) = (w/\Delta P)K \ge (V/A) + K'/\Delta P \qquad (a)$$

In the laboratory experiment  $w = w_I$ , and  $\Delta P = \Delta P_1$  $K = (0.0265\Delta P_1 / w_1)$  and  $K' = 1.6\Delta P_1$ 

For the new plant condition,  $w = w_2$  and  $P = P_2$ , so that, substituting in the eqn.(a) above, we then have for the plant filter, under the given conditions:

$$t/(V/A) = (0.0265 \,\Delta P_1/w_1)(w_2/\Delta P_2)(V/A) + (1.6\Delta P_1)(1/\Delta P_2)$$

and since from these conditions

and

$$\begin{split} \Delta P_1 / \Delta P_2 &= 340/270 \\ w_2 / w_1 &= 150/100, \\ t / (V/A) &= 0.0265(340/270)(150/100)(V/A) + 1.6(340/270) \\ &= 0.05(V/A) + 2.0 \\ t &= 0.5(V/A)^2 + 2.0(V/A). \end{split}$$

To find the volume that passes the filter in 1 h which is 3600s, that is to find V for t = 3600.

$$3600 = 0.05(V/A)^2 + 2.0(V/A)$$

and solving this quadratic equation, we find that V/A = 250kgm<sup>-2</sup>

and so the slurry passing through 9.3 m<sup>2</sup> in 1 h would be: =  $250 \times 9.3$ = 2325kg.

#### **Filter-cake Compressibility**

With some filter cakes, the specific resistance varies with the pressure drop across it. This is because the cake becomes denser under the higher pressure and so provides fewer and smaller passages for flow. The effect is spoken of as the compressibility of the cake. Soft and flocculent materials provide highly compressible filter cakes, whereas hard granular materials, such as sugar and salt crystals, are little affected by pressure. To allow for cake compressibility the empirical relationship has been proposed:

$$r = r' \Delta(P)^s$$

where *r* is the specific resistance of the cake under pressure *P*,  $\Delta P$  is the pressure drop across the filter, *r'* is the specific resistance of the cake under a pressure drop of 1atm and *s* is a constant for the material, called its compressibility.

This expression for r can be inserted into the filtration equations, such as eqn. (10.14), and values for r' and s can be determined by carrying out experimental runs under various pressures.

# **Filtration Equipment**

The basic requirements for filtration equipment are:

- mechanical support for the filter medium,
- flow accesses to and from the filter medium and
- provision for removing excess filter cake.

In some instances, washing of the filter cake to remove traces of the solution may be necessary. Pressure can be provided on the upstream side of the filter, or a vacuum can be drawn downstream, or both can be used to drive the wash fluid through.

#### Plate and frame filter press

In the plate and frame filter press, a cloth or mesh is spread out over plates which support the cloth along ridges but at the same time leave a free area, as large as possible, below the cloth for flow of the filtrate. This is illustrated in Fig. 10.8(a). The plates with their filter cloths may be horizontal, but they are more usually hung vertically with a number of plates operated in parallel to give sufficient area.

Filter cake builds up on the upstream side of the cloth, that is the side away from the plate. In the early stages of the filtration cycle, the pressure drop across the cloth is small and filtration proceeds at more or less a constant rate. As the cake increases, the process becomes more and more a constant pressure one and this is the case throughout most of the cycle. When the available space between successive frames is filled with cake, the press has to be dismantled and the cake scraped off and cleaned, after which a further cycle can be initiated.

The plate and frame filter press is cheap but it is difficult to mechanize to any great extent. Variants of the plate and frame press have been developed which allow easier discharging of the filter cake. For example, the plates, which may be rectangular or circular, are supported on a central hollow shaft for the filtrate and the whole assembly enclosed in a pressure tank containing the slurry.

Filtration can be done under pressure or vacuum. The advantage of vacuum filtration is that the pressure drop can be maintained whilst the cake is still under atmospheric pressure and so can be removed easily. The disadvantages are the greater costs of maintaining a given pressure drop by applying a vacuum and the limitation on the vacuum to about 80kPa maximum. In pressure filtration, the pressure driving force is limited only by the economics of attaining the pressure and by the mechanical strength of the equipment.





# Rotary filters

In rotary filters, the flow passes through a rotating cylindrical cloth from which the filter cake can be continuously scraped. Either pressure or vacuum can provide the driving force, but a particularly useful form is the rotary vacuum filter. In this, the cloth is supported on the periphery of a horizontal cylindrical drum that dips into a bath of the slurry. Vacuum is drawn in those segments of the drum surface on which the cake is building up. A suitable bearing applies the vacuum at the stage where the actual filtration commences and breaks the vacuum at the stage where the cake is being scraped off after filtration. Filtrate is removed through trunnion bearings. Rotary vacuum filters are expensive, but they do provide a considerable degree of mechanization and convenience. A rotary vacuum filter is illustrated diagrammatically in Fig. 10.8(b).

# Centrifugal filters

Centrifugal force is used to provide the driving force in some filters. These machines are really centrifuges fitted with a perforated bowl that may also have filter cloth on it. Liquid is fed into the interior of the bowl and under the centrifugal forces, it passes out through the filter material. This is illustrated in Fig. 10.8(c).

# Air filters

Filters are used quite extensively to remove suspended dust or particles from air streams. The air or gas moves through a fabric and the dust is left behind. These filters are particularly useful for the removal of fine particles. One type of bag filter consists of a number of vertical cylindrical cloth bags 15-30cm in diameter, the air passing through the bags in parallel. Air bearing the dust enters the bags, usually at the bottom and the air passes out through the cloth. A familiar example of a bag filter for dust is to be found in the domestic vacuum cleaner. Some designs of bag filters provide for the mechanical removal of the accumulated dust. For removal of particles less than  $5\mu$ m diameter in modern air sterilization units, paper filters and packed tubular filters are used. These cover the range of sizes of bacterial cells and spores.

# SIEVING

In the final separation operation in this group, restraint is imposed on some of the particles by mechanical screens that prevent their passage. This is done successively, using increasingly smaller screens, to give a series of particles classified into size ranges. The fluid, usually air, can effectively be ignored in this operation which is called sieving. The material is shaken or agitated above a mesh or cloth screen; particles of smaller size than the mesh openings can pass through under the force of gravity. Rates of throughput of sieves are dependent upon a number of factors:

- nature and shape of the particles,
- frequency and amplitude of the shaking,
- methods used to prevent sticking or bridging of particles in the apertures of the sieve and
- tension and physical nature of the sieve material.

Standard sieve sizes have evolved, covering a range from 25mm aperture down to about 0.6mm aperture. The mesh was originally the number of apertures per inch. A logical base for a sieve series would be that each sieve size have some fixed relation to the next larger and to the next smaller. A convenient ratio is 2:1 and this has been chosen for the standard series of sieves in use in the United States, the Tyler sieve series. The mesh numbers are expressed in terms of the numbers of opening to the inch (= 2.54 cm). By suitable choice of sizes for the wire from which the sieves are woven, the ratio of opening sizes has been kept approximately constant in moving from one sieve to the next. Actually, the ratio of 2:1 is rather large so that the normal series progresses in the ratio of  $\sqrt{2:1}$  and if still closer ratios are required

intermediate sieves are available to make the ratio between adjacent sieves in the complete set  $4\sqrt{2}$ : 1. The standard British series of sieves has been based on the available standard wire sizes, so that, although apertures are generally of the same order as the Tyler series, aperture ratios are not constant. In the SI system, apertures are measured in mm. A table of sieve sizes has been included in Appendix 10.

In order to get reproducible results in accurate sieving work, it is necessary to standardize the procedure. The analysis reports either the percentage of material that is retained on each sieve, or the cumulative percentage of the material larger than a given sieve size.

The results of a sieve analysis can be presented in various forms, perhaps the best being the cumulative analysis giving, as a function of the sieve aperture (D), the weight fraction of the powder F(D) which passes through that and larger sieves, irrespective of what happens on the smaller ones. That is the cumulative fraction sums all particles smaller than the particular sieve of interest.

Thus 
$$F = F(D)$$
,  
d $F/dD = F'(D)$ 

where F'(D) is the derivative of F(D) with respect to D.

So 
$$\int dF = \int F'(D) dD$$
 (10.15)

and so integrating between  $D_1$  and  $D_2$  gives the cumulative fraction between two sizes  $D_2$  (larger) and  $D_1$  which is also that fraction passing through sieve of aperture  $D_2$  and caught on that of aperture  $D_1$ . The F'(D) graph gives a **particle size distribution analysis**.

EXAMPLE 10.7. Sieve analysis Given the following sieve analysis:

| Sieve size    |            |
|---------------|------------|
| mm            | % Retained |
| 1.00          | 0          |
| 0.50          | 11         |
| 0.25          | 49         |
| 0.125         | 28         |
| 0.063         | 8          |
| Through 0.063 | 4          |
| -             |            |

plot a cumulative sieve analysis and estimate the weight fraction of particles of sizes between 0.300 and 0.350 mm and 0.350 and 0.400 mm.

From the above table:

| Less than aperture | (mm)  |            | 0.063 | 0.125 | 0.250 | 0.500                      | 1.00 |
|--------------------|-------|------------|-------|-------|-------|----------------------------|------|
|                    | (µm)  |            | 63    | 125   | 250   | 500                        | 1000 |
| Percentage (cumula | tive) |            | 4     | 12    | 40    | 89                         | 100  |
|                    |       | <b>T</b> . | 10.0  | 1.1   | 1     | $\mathbf{T}(\mathbf{D})$ 1 |      |

This has been plotted on Fig. 10.9 and the graph F(D) has been smoothed. From this the graph of F'(D) has been plotted, working from the slope of F(D), to give the particle size distribution.



Figure 10.9 Particle-size analysis

To find the fraction between the specified sizes, eqn. (10.15) indicates that this will be given directly by the fraction, that the area under the F'(D) graph and between the sizes of interest, is to the total area under the F'(D) curve. Counting squares, on Fig. 10.9, gives:

between 300µm (0.300 mm) and 350µm (0.350mm) as 13% and 350µm (0.350mm) and 400µm (0.400mm) as 9%.

For industrial sieving, it is seldom worthwhile to continue until equilibrium is reached. In effect, a sieving efficiency term is introduced, as a proportion only of the particles smaller than a given size actually get through. The sieves of a series are often mounted one above the other, and a mechanical shaker used.

Sieve analysis for particle size determination should be treated with some caution especially for particles deviating radically from spherical shape, and it needs to be supplemented with microscopical examination of the powders. The size distribution of powders can be useful to estimate parameters of technological importance such as the surface area available for a reaction, the ease of dispersion in water of a dried milk powder, or the performance characteristics of a spray dryer or a separating cyclone.

Industrial sieves include rotary screens, which are horizontal cylinders either perforated or covered with a screen, into which the material is fed. The smaller particles pass through as they tumble around in the rotating screens. Other industrial sieves are vibrating screens, generally vibrated by an eccentric weight; and multi-deck screens on which the particles fall through from one screen to another, of decreasing apertures, until they reach one which is too fine for them to pass. With vibrating screens, the frequency and amplitude of the vibrations can significantly affect the separation achieved. Screen capacities are usually rated in terms

of the quantity passed through per unit area in unit time. Particles that can conveniently be screened industrially range from 50µm diameter, upwards.

Continuous vibrating sieves used in the flour-milling industry employ a sieve of increasing apertures as particles progress along the length of the screen. So the finer fraction at any stage is being removed as the flour particles move along. The shaking action of the sieve provides the necessary motion to make the particles fall through and also conveys the oversize particles on to the next section. Below the sieves, in some cases, air classification may be used to remove bran.

#### SUMMARY

- 1. Particles can be separated from fluids, or particles of different sizes from each other, making use of forces that have different effects depending on particle size.
- 2. Flow forces in fluids give rise to velocities of particles relative to the fluid of:

$$v_m = D^2 a (\rho_p - \rho_f) / 18 \mu$$

Where the particle is falling under gravity a = g, so giving Stokes' Law

$$v_m = D^2 g(\rho_p - \rho_f) / 18 \mu$$

3. Continuous thickeners can be used to settle out solids, and the minimum area of a continuous thickener can be calculated from:

$$v = (F - L)(dw/dt)/A\rho$$

4. Gravitational and centrifugal forces can be combined in a cyclone separator.

$$F_{\rm c} = (mv^2)/r$$

5. In a centrifuge, the force relative to the force of gravity is given by  $(0.011 rN^2)/g$  and the steady state velocity:

$$v_m = D^2 N^2 r (\rho_p - \rho_f) / 1640 \mu$$

6. In centrifugal separation of liquids, the radius of the neutral zone:

$$r_{\rm n}^2 = (\rho_{\rm A} r_1^2 - \rho_{\rm B} r_2^2) / (\rho_{\rm A} - \rho_{\rm B})$$

7. In a filter, the particles are retained and the fluid passes at a rate given by:

$$dV/dt = A\Delta P/\mu r[w(V/A) + L]$$

8. Sieve analysis can be used to estimate particle size distributions. In cumulative sieve analysis:

$$\int \mathrm{d}F = \int F''(D) \,\mathrm{d}D$$

integrating between  $D_1$  and  $D_2$ 

#### PROBLEMS

1. A test was carried out on a wine filter. It was found that under a constant pressure difference of 350kPa gauge, the rate of flow was 450kg h<sup>-1</sup> from a total filter area of

 $0.82m^2$ . Assuming that the quantity of cake is insignificant in changing the resistance of the filter, if another filter of 6.5 m<sup>2</sup> area is added, what pressure would be required for a throughput of 500 hectolitres per 8-hour shift from the combined plant? Firstly determine *R*, the resistance, and then the pressure difference. Assume density of wine is 1000kgm<sup>3</sup>.

- 2. A wine clarifying filter, on checking, is found to pass 500 l/h under a pressure differential of 220 kPa. If 1200 l of wine with twice the degree of cloudiness has to be passed through the filter how long would you expect this to take? If you wished to complete this filtration in a 1 hour cycle, calculate the pressure you would need to apply.
- 3. Calculate the settling velocity of sand particles 0.2mm diameter in 22% salt solution of density 1240kgm<sup>-3</sup> at 20°C. Take the density of sand as 2010kgm<sup>-3</sup>.
- 4. In a trough, 0.8 m long, there is a slowly (0.01ms<sup>-1</sup>) flowing 22% salt solution. If it was desired to settle out sand particles, with which the solution had become contaminated, estimate the smallest diameter of sand particle that would be removed.
- 5. It is desired to establish a centrifugal force of 6000g in a small centrifuge with an effective working radius of 9cm. At what speed would the centrifuge have to rotate?

If the actual centrifuge bowl has a radius of 8cm minimum and 9 cm maximum what is the difference in the centrifugal force between the minimum and the maximum radii?

- 6. In a centrifuge separating oil (of density 900kg m<sup>-3</sup>) from brine (of density 1070kg m<sup>-3</sup>), the discharge radius for the oil is 5cm. Calculate a suitable radius for the brine discharge and for the feed intake so that the machine will work smoothly assuming that the volumes of oil and of brine are approximately equal.
- 7. If a centrifuge is regarded as similar to a gravity settler but with gravity replaced by the centrifugal field, calculate the area of a centrifuge of working radius r and speed of rotation N revolutions min<sup>-1</sup> that would have the same throughput as a gravity settling tank of area  $100m^2$ .
- 8. If an olive oil/water emulsion of  $5\mu$ m droplets is to be separated in a centrifuge into oil and water, what speed (revs min<sup>-1</sup>) would be necessary if the effective working radius of the centrifuge is 5cm? Assume that the necessary travel of the droplets is 3 cm and this must be done in 1 second to cope with the throughput in a continuous centrifuge.
- 9. A sieve analysis gives the following results:

| Sieve size    | Wt. retained |
|---------------|--------------|
| mm            | g            |
| 1.00          | 0            |
| 0.500         | 64           |
| 0.250         | 324          |
| 0.125         | 240          |
| 0.063         | 48           |
| Through 0.063 | 24           |
|               |              |

Plot a cumulative size analysis and a size-distribution analysis, and estimate the weights, per 1000kg of powder, which would lie in the size ranges 0.150 to 0.200 mm and 0.250 to 0.350 mm.

11. If a dust, whose particle size distribution is as in the table below, is passed through a cyclone with collection efficiency as shown in Fig. 10.2 estimate the size distribution of the dust passing out.

| Particle diameter   | <0.5µm | 3µm | 6µm | l0µm | l5µm | 25µm |
|---------------------|--------|-----|-----|------|------|------|
| Wt. of particles kg | 0.2    | 0.7 | 0.4 | 0.2  | 0.1  | 0    |