06

Mass Transfer and Its Applications

Objectives

When you have completed study of this chapter you should be able to:

- Understand the concept of mass transfer;
- Apply the fundamentals of mass transfer in chemical process industries;
- Know the different equipments used for mass transfer applications.

6.1 Mass Transfer Fundamentals

A group of unit operations for separating the components of mixtures is based on the transfer of material from one homogenous phase to another. The driving force for transfer is a concentration difference or a concentration gradient; much like a temperature difference or a temperature gradient provides the driving force for heat transfer. These methods, covered by the term mass-transfer operations, include such techniques as indicated below:

- Distillation
- Gas absorption
- Dehumidification
- Liquid extraction
- Leaching
- Drying

6.2 Distillation

The purpose of distillation is to separate, by vaporization, a liquid mixture of miscible and volatile substances into individual components or, in some cases, into groups of components. The separation of a mixture of alcohol and water into its components; of air into nitrogen, oxygen, and argon; and of crude petroleum into gasoline, kerosene, fuel oil, and lubricating stock are examples of distillation.

6.2.1 Typical Distillation Equipment

A process system for continuous distillation is shown in Fig. 6-1. Reboiler A is fed continuously with the liquid mixture to be distilled. The liquid is converted partially into vapor by heat transferred from the heating surface B. The vapor formed in the reboiler is richer than the unvaporized liquid, but unless the two components differ greatly in volatility, the vapor contains substantial quantities of both components, and if it were condensed, the condensate would be far from pure. To increase the concentration of low boiler in the vapor, the vapor stream from the still is brought into intimate countercurrent contact with a descending stream of boiling liquid in the column, or tower, C. This liquid must be rich enough in low boiler so that there is mass transfer of the low boiler from the liquid to vapor at each stage of the column. Such a liquid can be obtained simply by condensing the overhead vapors and returning some of the liquid to the top of the column. This return liquid is called reflux. The use of reflux increases the purity of the overhead product, but not without some cost, since the vapor generated in the reboiler must provide both reflux and overhead product, and this energy cost is a large part of the total cost of separation by distillation.

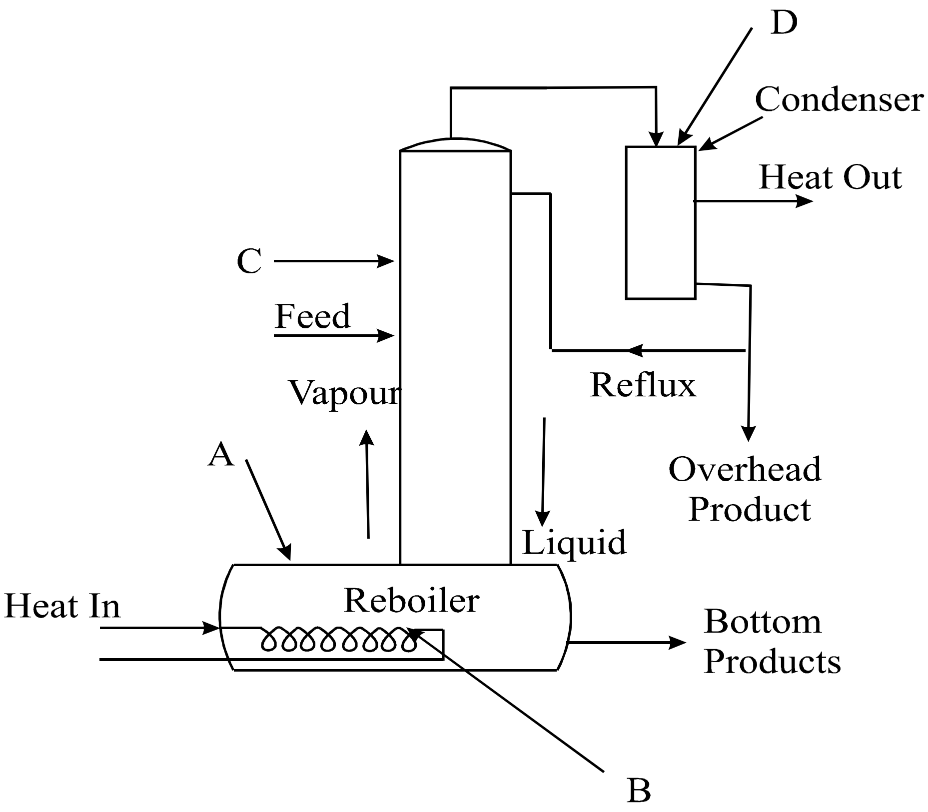

Figure 6.1
Reboiler With Fractionating Column

The reflux entering the top of the column is often at the boiling point; but if it is cold, it is almost immediately heated to its boiling point by the vapor. Throughout the rest of the column, the liquid and vapor are at their boiling and condensing temperatures respectively, and the temperatures increase on going down the column because of the increase in high boiler concentration, and in some cases, because of increase in pressure.

Enrichment of the vapor occurs at each stage because the vapor coming to a stage has a lower concentration of the low boiler than the vapor that would be in equilibrium with the liquid fed to that stage. For example, considering the top stage, the vapor coming to this stage is less rich than the overhead product, and the reflux, which has the same composition as the product, has an equilibrium vapor composition, which is even richer than the product. Therefore, vapor passing through the top stage will be enriched in low boiler at the expense of the reflux liquid. This makes the reflux poorer in low boiler, but if the flow rates have been adjusted correctly, the liquid passing down to the second stage will still be able to enrich the lower quality vapor coming up to the second stage. Then at all stages in the column, some low boiler diffuses from the liquid into the vapor phase, and there is a corresponding diffusion of high boiler from the vapor to the liquid. The heat of vaporization of the low boiler is supplied by the heat of condensation of the high boiler, and the total flow rate of vapor up the column is nearly constant.

The enrichment of the vapor stream as it passes through the column in contact with reflux is called rectification. It is immaterial where the reflux originates, provided its concentration in low boiler is sufficient to give the desired product. The usual source of reflux is the condensate-leaving condenser D. Part of the condensate is withdrawn as the product, and the remainder returned to the top of the column reflux is sometimes provided by partial condensation of the overhead vapor; the reflux then differs in composition from the vapor leaving as overhead product. Provided an azeotrope is not formed, the vapor reaching the condenser can be brought as close to complete purity as desired by using a tall tower and a large reflux.

From the reboiler, liquid is withdrawn which contains most of the high boiling component, because little of this component escapes with the overhead product unless the product is an azeotrope. The liquid from the reboiler, which is called the bottom product or bottoms, is not nearly pure, however, because there is no provision in the equipment of Figure 6-1 for rectifying this stream.

The column shown in Figure 6.1 often contains a number of perforated plates, or trays, stacked one above the other. A cascade of such trays is called a sieve-plate column. A single sieve plate is shown in Figure 6.2. It consists of a horizontal tray A carrying a down pipe, or downcomer C, the top of which acts as a weir, and a number of holes B. The holes are all the same size, usually 1/4 to 1/2 inch in diameter. The downcomer D from the tray above reaches nearly to tray A. This construction leads to the following flow of liquid and vapor. Liquid flows from plate to plate down the column, passing through downcomers D and C and across the plates. The weir maintains a minimum depth of liquid on the tray, nearly independent of the rate of flow of liquid. Vapor flows upward from tray to tray through the perforations. Except at very low vapor rates, well below the normal operating range, the vapor velocity through the perforations is sufficient to prevent leakage or "weeping" of the liquid through the holes. The vapor is subdivided by the holes into many small bubbles and passes in intimate contact through the pool of liquid on the tray. Because of the action of the vapor bubbles, the liquid is actually a boiling, frothy mass. Above the froth and below the next tray is fog from collapsing bubbles. This fog for the most part settles back into the liquid, but some is entrained by the vapor and carried to the plate above. Sieve-plate columns are representative of an entire class of equipment called plate columns.

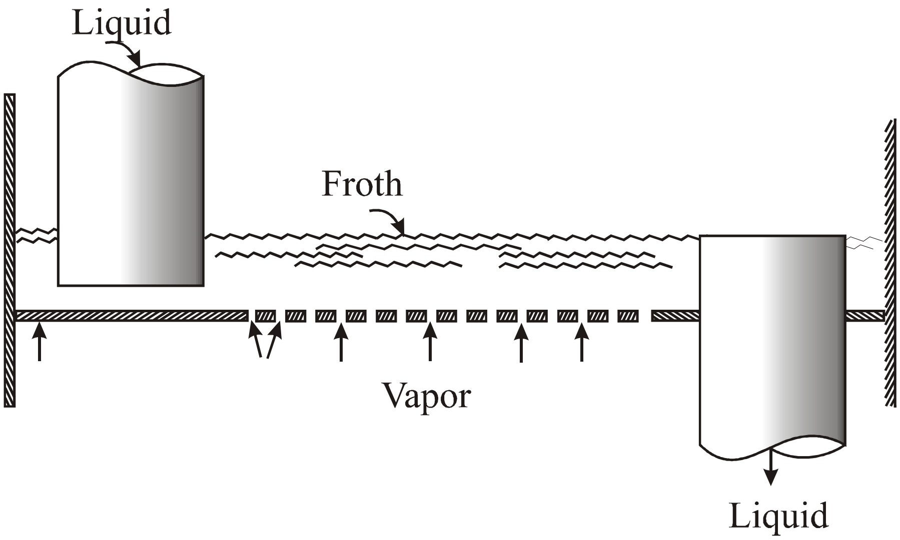

Figure 6.2
Sieve Plate

Flash Distillation

Flash distillation consists of vaporizing a definite fraction of the liquid in such away that the evolved vapor is in equilibrium with the residual liquid, separating the vapor from the liquid, and condensing the vapor. Figure 6.3 shows the elements of a flash-distillation plant. Feed is pumped by pump through a heater, and the pressure is reduced through valve. An intimate mixture of vapor and liquid enters the vapor separator, in which sufficient time is allowed for the vapor and liquid portions to separate. Because of the intimacy of contact of liquid and vapor before separation, the separated streams are in equilibrium.

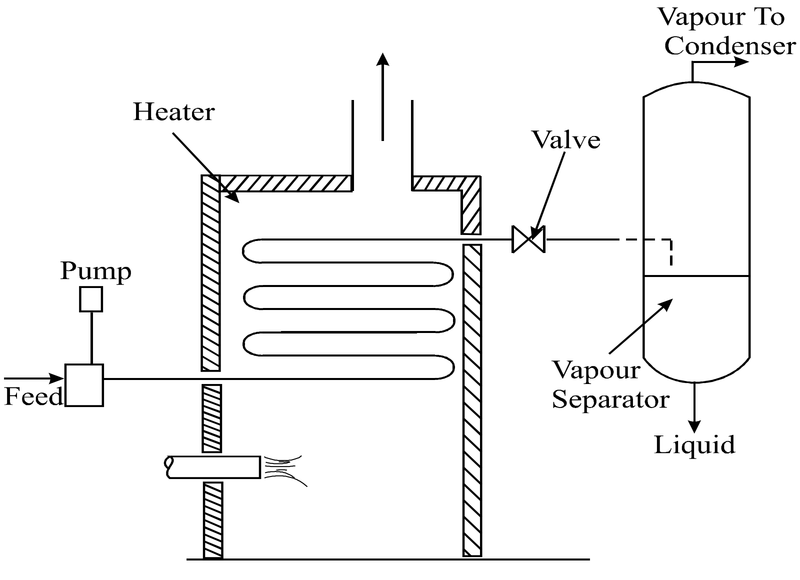

Figure 6.3
Plant for Flash Distillation

Osmosis Distillation

Osmosis denotes the movement of water down a concentration gradient. Water moving from an area of high concentration to an area of lower concentration. So how does osmotic distillation differ? Rather than using concentration gradients as a driving force, osmotic distillation uses the differences in vapor pressures of the contacting liquid phases. This allows actual separation of water from other components without the other components "following" the water as it moves. This is particularly useful in concentrating food and pharmaceutical products that are sensitive to elevated temperatures.

A liquid phase with one or more volatile components is separated from a salt solution by a non-wetting polymer membrane. The membrane is typically made of non-polar polymers such as polyethylene, polypropylene, or PTFE.

This membrane functions as a vapor barrier between the liquid phases. The salt solution is usually composed of sodium or calcium chloride. Figure 6.4 shows the interface arrangement used in osmotic distillation.

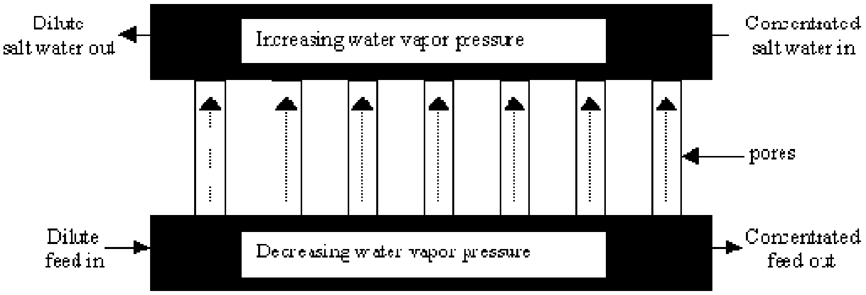

Figure 6.4
Interface Arrangement of Osmotic Distillation

Mechanism

Water moves across the osmotic distillation (OD) membrane by evaporating, diffusing through the pores, and condensing on the other side of the pores. The liquid is prohibited from entering the pores by membrane design. The membrane is designed such that the liquids cannot exceed the capillary forces required to enter the pores. Design factors include surface tension, contact angle, capillary pressure, and pore radius. The heat of vaporization is supplied by conduction or convection from the upstream liquid through the membrane. The temperature gradient across the membrane is typically less than 2 ^{0}C making the process nearly isothermal.

Exclusive Transport of Water

When OD is performed at low temperatures the vapor pressures of components (other than water) are substantially low (relative to water). This reduces the driving force for those components to pass through the membrane. As an example, we'll compare the vapor pressure of water with acetic acid at 30 ^{0}C. The vapor pressure of water at this temperature is 32 mm Hg while acetic acid has a vapor pressure of 20 mm Hg. Some larger biological molecules found in pharmaceuticals would have an even lower vapor pressure at 30 ^{0}C. In addition to this mechanism, most of solutes in the water have lower solubilities in the salt solution than in water. This also aids in keeping the solutes in place while they are being concentrated.

Figure 6.5 below shows a typical setup used in osmotic distillation.

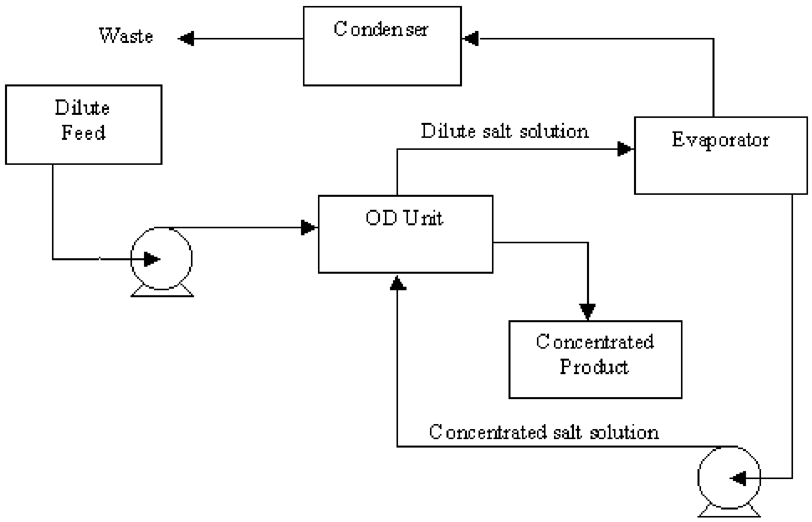

Figure 6.5
Typical Setup Used in Osmotic Distillation

Osmotic distillation provides a means of purifying heat sensitive substances including pharmaceuticals and biological products. Increased costs involved with OD separation will not allow this technology to rival ultrafiltration and reverse osmosis when these processes provide the necessary purity. There are however many applications where OD offers many advantages over other separation technologies. This has produced significant interest in OD by pharmaceutical companies in particular.

6.2.2 Energy Conservation in Distillation

Distillation is the preferred method of separation in a chemical process industry. as it is a very energy intensive process. Fine-tuning distillation columns (and in some cases, making major changes) can considerably save a company's expenditure . Consider the following distillation column:

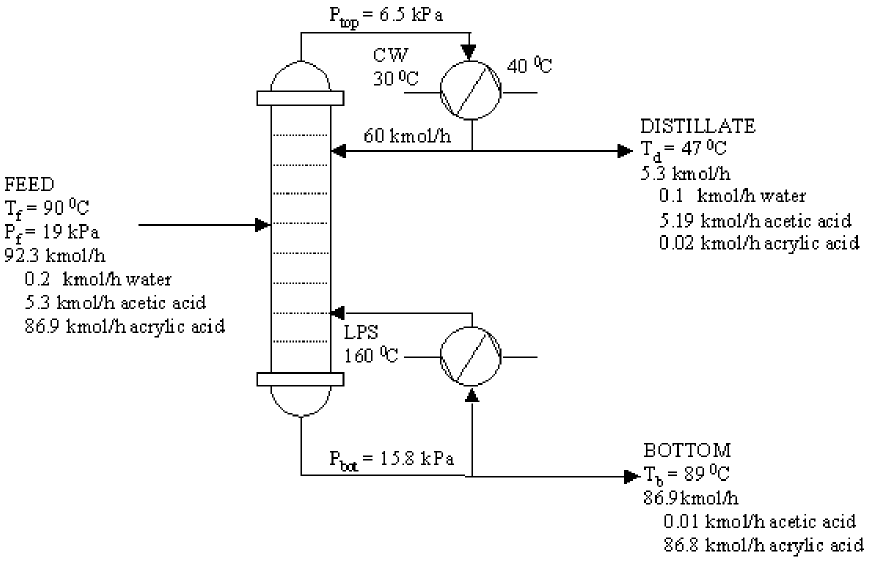

Figure 6.6
Elementary Column Arrangement

Feed Temperature (^{0}C)	90.0
Feed Pressure (kPa)	19.0
Top Pressure (kPa)	6.5
Bottom Pressure (kPa)	15.8
Reflux Ratio	12.2
R/Rmin	1.18
Feed Stage	9
Number of Actual Trays	31
Tray Efficiency	78%
Diameter (m)	1.2
Length (m)	22
Flooding	53%
Condenser Heat Duty (MJ/h)	-2726
Reboiler Heat Duty (MJ/h)	2679
Acrylic Acid Purity	99.9%

Table 6.1
Column Design Specifications

An examination of this column reflects how small changes can save operating cost .

1. Check product purity (Rating: Minimal or No Investment)

Many companies tend to excessively purify products and sometimes with a specific reason. However, purifying to 98% when 95% is acceptable is just not necessary. In this case, the reflux rate should be decreased in small increments until the desired purity is obtained.

2. *Seasonal Operating Pressure Adjustments (Rating: Minimal or No Investment)*

For plants that are in locations that experience winter climates, the operating pressure can be reduced according to a decrease in cooling water temperatures. Although lowering the pressure in our column would actually be an expense since it's under vacuum, this would not always be the case. The lower pressure will facilitate separation thus lowering energy consumption.

Hence it is wise decision to take advantage of lower temperatures outside.

3. *Upgrading Column Internals (Rating: Moderate Investment)*

Damaged or worn internals can turn your distillation column into a money pit. As the internals become damaged, efficiency decreases and pressure drops rise. This in turn causes the column to run at a higher reflux rate over time. With an increased reflux rate, energy costs will increase accordingly. Replacing the trays with new ones or adding high performance packing can have the column operating like the day it was brought online.

Therefore If the operating conditions have seriously deviated from designed operating conditions, this moderate investment can be well worth the price tag in the long run.

4. *Improved Heat Integration (Rating: High Investment)*

In many cases, the overhead product can be used to preheat the feed stream of distillation columns. This yields reductions in both condenser and reboiler utilities. Of course, there may be many other opportunities for heat integration.

A good economic analysis of this option will tell you if it's right for your situation.

5. *Upgrading the Control System (Rating: High Investment)*

Despite a perfectly designed column will not utilize energy inputs properly under a poor control system. The concept is quite simple, the less advanced your control system is, the more decisions that DCS (Distributed Control Systems) operators must make. Unfortunately, even the most senior operators will find it difficult to operate a column at its optimal energy input levels. Upgrading your control system, especially those columns with older controllers, can bring your column to its optimal operating points.

Older control systems cannot last forever. Check the design specifications and see where your column is operating.

6.3 Leaching And Extraction

Leaching normally refers to the removal of a substance from a solid via a liquid extraction media. The desired component diffuses into the solvent from its natural solid form. Examples of leaching include the removal of sugar from sugar beets with hot water and the removal of nickel salts or gold from their natural solid beds with sulfuric acid solutions.

There are many different types of equipment used for leaching. Most of these pieces of equipment fall into one of two categories:

- Whether the leaching is taking place via percolation or by dispersed-solids, there are three important factors that aid in leaching: temperature, contact time/area, and solvent selection. Temperature is adjusted to optimize solubility and mass transfer

- Liquid-to-solid contact is essential for the extraction to take place and maximize contact area per unit volume reduces equipment size. Solvent selection plays an important role in solubilities as well as the separation steps that follow leaching. Nearly all leaching equipment employs some type of agitation to aid in mass transfer and to ensure proper mixing

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6.3.1 Leaching by Percolation

Stationary solid-bed leaching is done in a tank with a perforated false bottom to support the solids and permit drainage of the solvent. Solids are loaded into the tank, sprayed with solvent until their Solute content is reduced to the economical minimum, and excavated. In some cases the rate of solution is so rapid that one passage of solvent through the material is sufficient, but countercurrent flow of solvent through a battery of tanks is more common. In this method, fresh solvent is fed to the tanks in series and is finally withdrawn from the tank that has been freshly charged. Such a series of tanks is called an extraction battery. The solid in any one tank is stationary until it is completely extracted. The piping is arranged so that fresh solvent can be introduced to any tank and strong solution withdrawn from any tank, making it possible to charge and discharge one tank at a time. The other tanks in the battery are kept in countercurrent operation by advancing the inlet and draw-off tanks one at a time as the material is charged and removed. Such a process is sometimes called a *Shanks process*.

In some solid-bed leaching the solvent is volatile, necessitating the use of closed vessels operated under pressure. Pressure is also needed to force solvent through beds of some less permeable solids. A series of such pressure tanks operated with countercurrent solvent flow is known as a diffusion battery.

6.3.2 Moving Bed Leaching

The bollman extractor shown in Figure 6.7 consists of a U-shaped screw conveyor with a separate helix in each section. The helices turn at different speeds to give considerable compaction of the solids in the horizontal section.

Solids are fed to one leg of the U and fresh solvent to the other to give countercurrent flow.

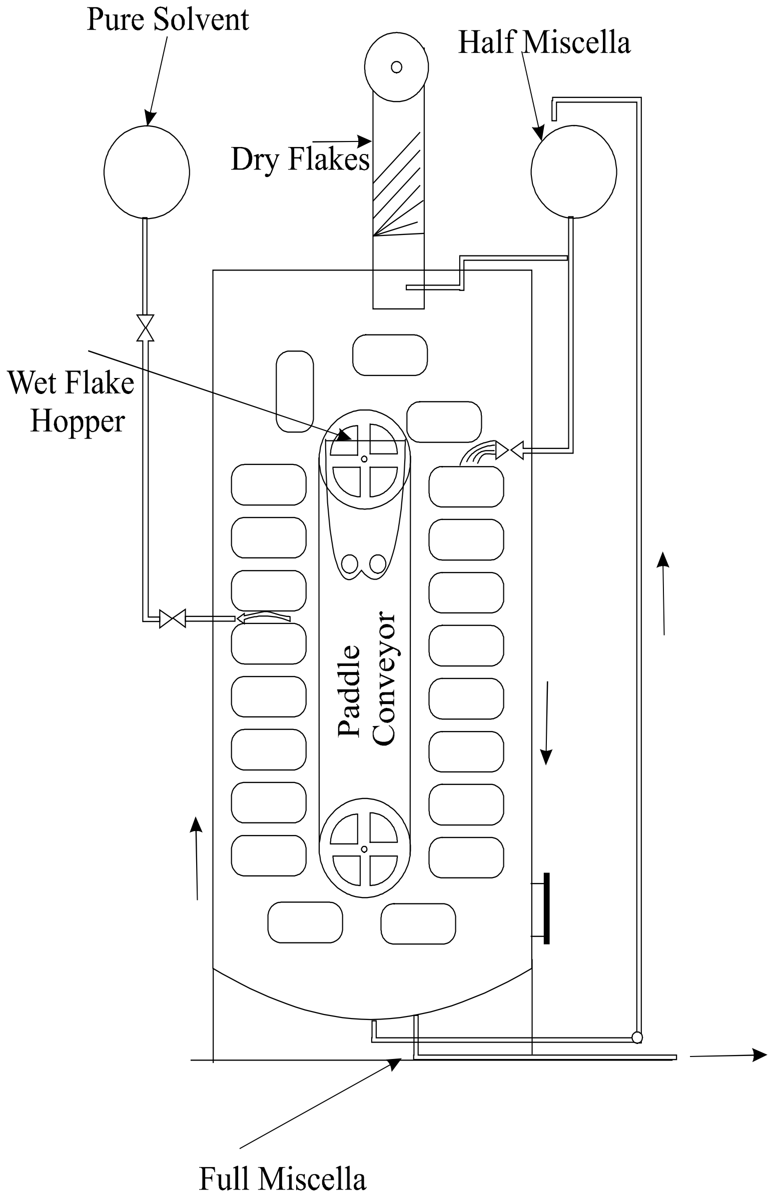


Figure 6.7
Bollman Extractor

6.3.3 Counter Current Leaching Plant

In leaching, soluble material is dissolved from its mixture with an inert solid by means of a liquid solvent. A diagrammatic flow sheet of a typical countercurrent leaching plant is shown in Fig.6.8. It consists of a series of units, in each of which the solid from the previous unit is mixed with the liquid from the succeeding unit and the mixture allowed to settle. The solid is then transferred to the next succeeding unit, and the liquid to the previous unit. As the liquid flows from unit to unit, it becomes enriched in solute, and as the solid flows from unit to unit in the reverse direction, it becomes impoverished in solute. The solid discharged from one end of the system is well extracted, and the solution leaving at the other end is strong in solute. The thoroughness of the extraction depends on the amount of solvent and the number of units. In principle, the unextracted solute can be reduced to any desired amount if enough solvent and a sufficient number of units are used.

Any suitable mixer and settler can be chosen for the individual units in a countercurrent leaching system. In those shown in fig. 6.8 mixing occurs in launders A and in the tops of the tanks, rakes B move solids to the discharge, and slurry pumps C move slurry from tank to tank.

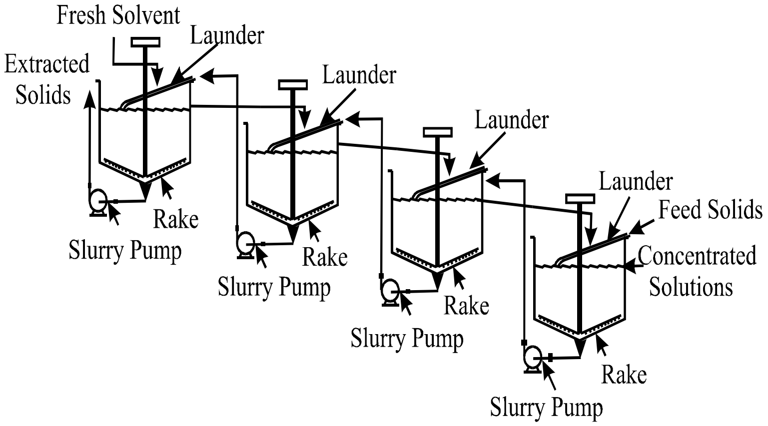


Figure 6.8
Counter Current Leaching Plant

6.3.4 Mixer-settlers

For a batch wise extraction the mixer and settler may be the same unit. A tank containing a turbine or propeller agitator is most common. At the end of the mixing cycle the agitator is shut off, the layers allowed to separate by gravity, and extract and raffinate drawn off to separate receivers through a bottom drain line carrying a slight glass. The mixing and settling times required for a given extraction can be determined only by experiment; 5 min for mixing and 10 min for settling are typical, but both shorter and much longer times are common.

For continuous flow, the mixer and settler must be separate pieces of equipment. The mixer may be a small-agitated tank provided with inlets and a draw-off line and baffles to prevent short-circuiting; or it may be a centrifugal pump or other flow mixer. The settler is often a simple continuous gravity decanter. With liquids, which emulsify easily and which have nearly the same density it may be necessary to pass the mixer discharge through a screen or pad of glass fiber to coalesce the droplets of the dispersed phase before gravity settling is feasible. For even more difficult separations, tubular or disk-type centrifuges are employed.

6.3.5 Spray and Packed Extraction Towers

These tower extractors give differential contacts, not stage contacts, and mixing and settling proceed simultaneously and continuously. In the spray tower shown in Fig. 6.9, the lighter liquid is introduced at the bottom and distributed as small drops by a nozzles.

The drops of light liquid rise through the mass of heavier liquid, which flows downward as a continuous stream. The drops are collected at the top and form the stream of light liquid leaving the top of the tower. The heavy liquid leaves the bottom of the tower. In Fig. 6.9, light phase is dispersed and heavy phase is continuous. This may be reversed, and the heavy stream sprayed into the light phase at the top of the column, to fill as dispersed phase through a continuous stream of light liquid. The choice of dispersed phase depends on the flow rates, viscosities, and wetting characteristics of both phases and is usually based on experience. The phase with the higher flow rate may be dispersed to give a greater interfacial area, but if there is a significant difference in viscosities, the more viscous phase may be dispersed to give a higher settling rate. Some say the continuous phase should wet the packing, but this need not be true for good performance. Whichever phase is dispersed, the movement of drops through the column constantly brings the liquid in the dispersed phase into fresh contact with the other phase to give the equivalent of a series of mixer-settlers.

There is a continuous transfer of material between phases, and the composition of each phase changes as it flows through the tower. At any given level, of course, equilibrium is not reached; indeed, it is the departure from equilibrium that provides the driving force for material transfer. The rate of mass transfer is relatively low compared to distillation or absorption, and a tall column may be equivalent to only a few perfect stages.

In actual spray towers, contact between the drops and the continuous phase often appears to be most effective in the region where the drops are formed. This could be due to a higher rate of mass transfer in newly formed drops or to back mixing of the continuous phase. In any case, adding more height does not give a proportional increase in the number of stages; it is much more effective to redisperse the drops at frequent intervals throughout the tower. This can be done by filling the tower with packing, such as rings or saddles. The packing causes the drops to coalesce and reform and, may increase the number of stages in a given height of column. Packed towers resemble spray towers in simplicity and can be made to handle almost any problem of corrosion or pressure at a reasonable cost. Their chief disadvantage is that solids tend to collect in the packing and cause channeling.

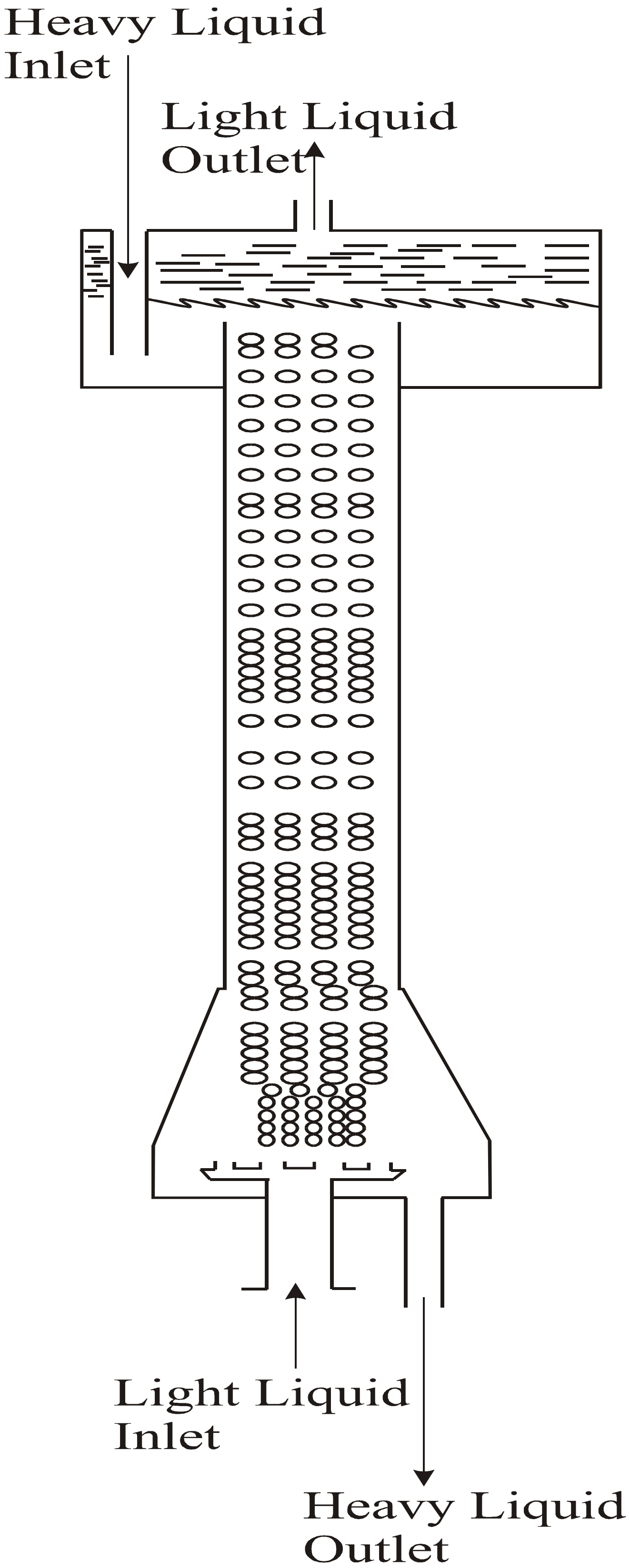


Figure 6.9
Spray Tower

6.3.6 Centrifugal Extractors

The dispersion and separation of the phases may be greatly accelerated by centrifugal force, and several commercial extractors make use of this. In the Podbielniak extractor, a perforated spiral ribbon inside a heavy metal casing is wound around a hollow horizontal shaft through which the liquids enter and leave. Light liquid is pumped to the outside of the spiral at a pressure between 3 and 12 atm to overcome the centrifugal force; heavy liquid is pumped to the center. The liquids flow counter currently through the passage formed by the ribbon and the casing walls. Heavy liquid moves outward along the outer face of the spiral; light liquid is forced by displacement to flow inward along the inner face. The high shear at the liquid-liquid interface results in rapid mass transfer.

6.4 Gas Absorption

6.4.1 Design of Packed Towers

A common apparatus used in gas absorption and certain other operations is the packed tower, an example of which is shown in Fig.6.10 . The device consists of a cylindrical column, or tower, equipped with a gas inlet and distributing space at the bottom; a liquid inlet and distributor at the top; gas and liquid outlets at the top and bottom respectively; and a supported mass of inert solid shapes, called tower packing. The support should have a large fraction of open area, so that flooding does not occur at the support plate. The inlet liquid, which may be pure solvent or a dilute solution of solute in the solvent and which is called the weak liquor, is distributed over the top of the packing by the distributor and, in ideal operation, uniformly wets the surfaces of the packing. The solute-containing gas, or rich gas, enters the distributing space below the packing and flows upward through the interstices in the packing countercurrent to the flow of the liquid. The packing provides a large area of contact between the phases. The solute in the rich gas is absorbed by the fresh liquid entering the tower, and diluted, or lean gas, leaves the top. The liquid is enriched in solute as its flows down the tower, and concentrated liquid, called strong liquor, leaves the bottom of the tower through the liquid outlet.

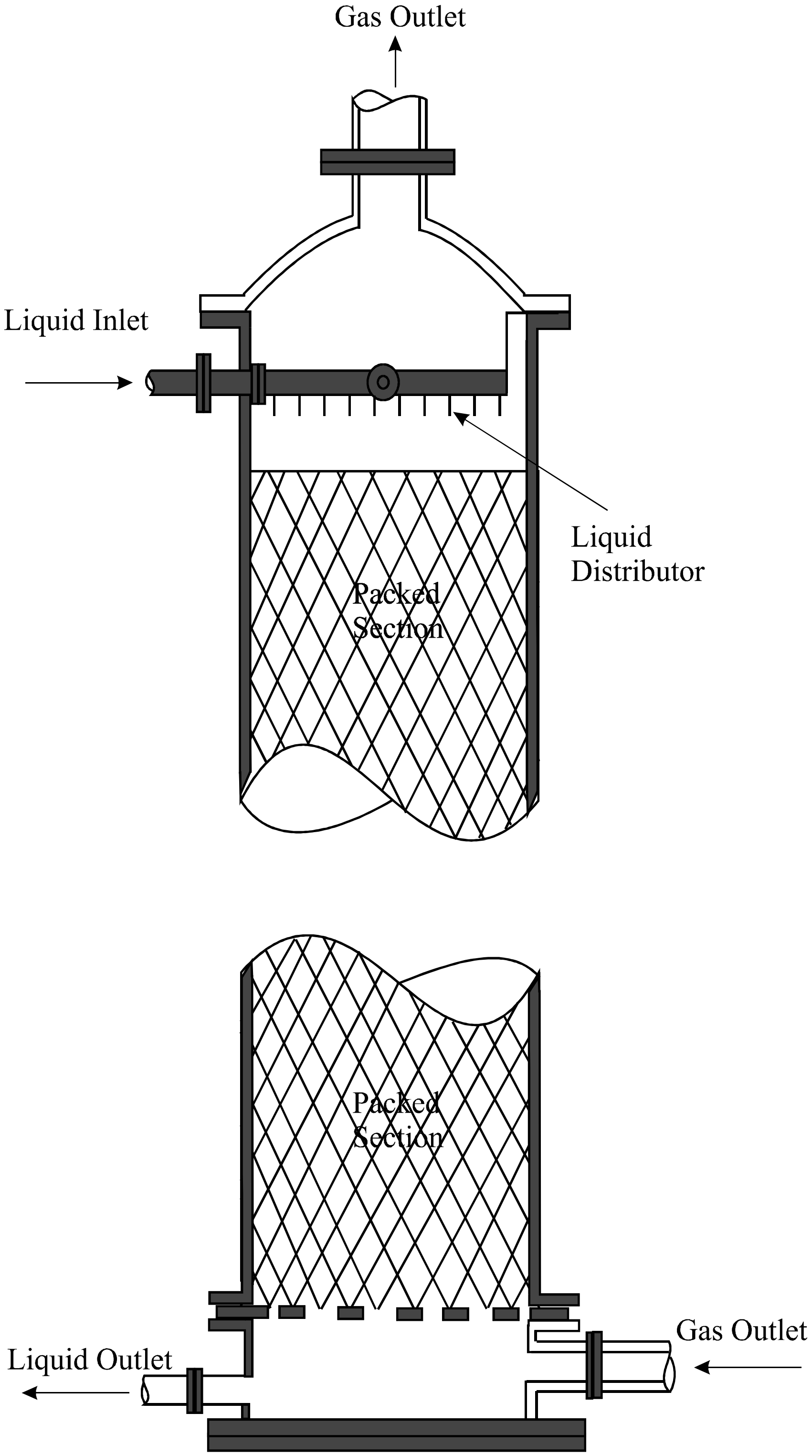


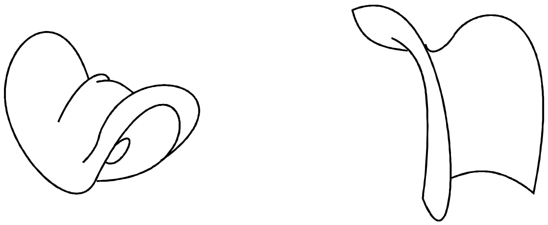
Figure 6.10
Packed Tower

6.4.2 Tower Packings

Many kinds of tower packing have been invented, and several types are in common use. Packings are divided into those which are dumped at random into the tower and those which must be stacked by hand. Dumped packings consist of units 1/4 to 3 in. in major dimension; packings smaller than 1 in. are used mainly in laboratory or pilot-plant columns. The units in stacked packings are 2 to about 8 inches in size. Common packings are illustrated in Fig. 6.11.

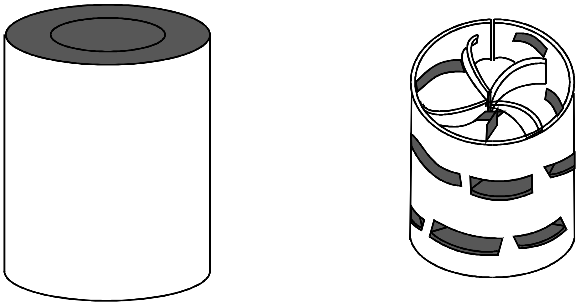
The principal requirements of a tower packing are

- It must be chemically inert to the fluids in the tower.
- It must be strong without excessive weight.
- It must contain adequate passages for both streams without excessive liquid holdup or pressure drop.
- It must provide good contact between liquid and gas.
- It must be reasonable in cost.



Berl Saddle

Ceramic Intalox Saddle



Raschig Rings

Metal Pall Ring

Figure 6.11
Typical Tower Packing

6.5 Humidification Operations

6.5.1 Cooling Towers

Cooling towers are a very important part of many chemical plants. They represent a relatively inexpensive and dependable means of removing low grade heat from cooling water

Design and Operation Considerations

The make-up water source is used to replenish water lost to evaporation. Hot water from heat exchangers is sent to the cooling tower. The water exits the cooling tower and is sent back to the exchangers or to other units for further cooling

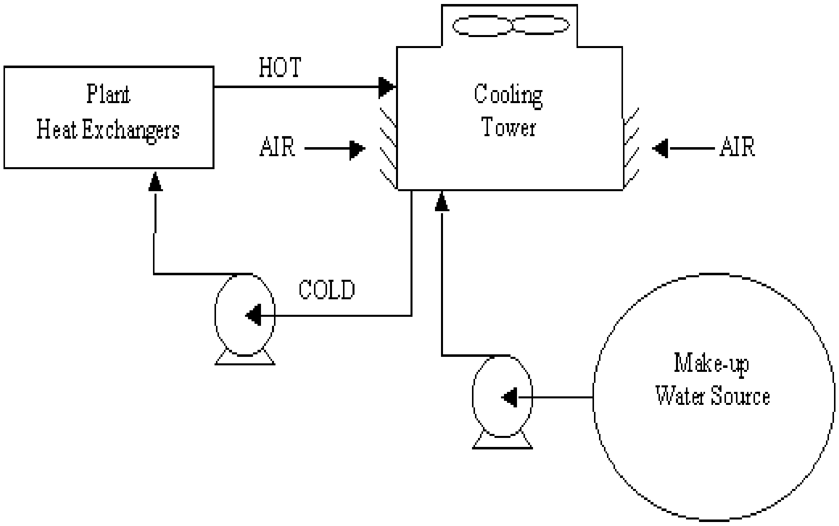
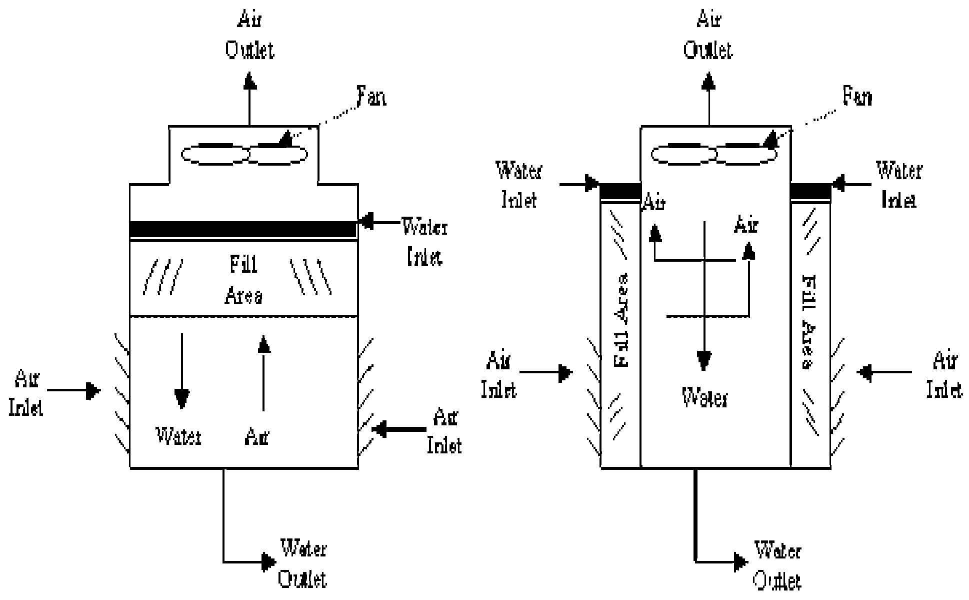


Figure 6.12
A Closed Loop Cooling Tower System

Types of Cooling Towers

Cooling towers fall into two main sub-divisions: natural draft and mechanical draft. Natural draft designs use very large concrete chimneys to introduce air through the media. Due to the tremendous size of these towers (500 ft high and 400 ft in diameter at the base) they are generally used for water flow rates above 200,000 gal/min. Usually these types of towers are only used by utility power stations in the United States. Mechanical draft cooling towers are much more widely used. These towers utilize large fans to force air through circulated water. The waterfalls downward over fill surfaces, which help, increase the contact time between the water and the air. This helps maximize heat transfer between the two.



(A) **(B)**

Figure 6.13 (A)
Mechanical Draft Counterflow Tower

Figure 6.13 (B)
Mechanical Draft Crossflow Tower

Mechanical draft towers offer control of cooling rates in their fan diameter and speed of operation. These towers often contain several areas (each with their own fan) called ***cells***.

A typical natural-draft cooling tower is shown in fig 6.14.

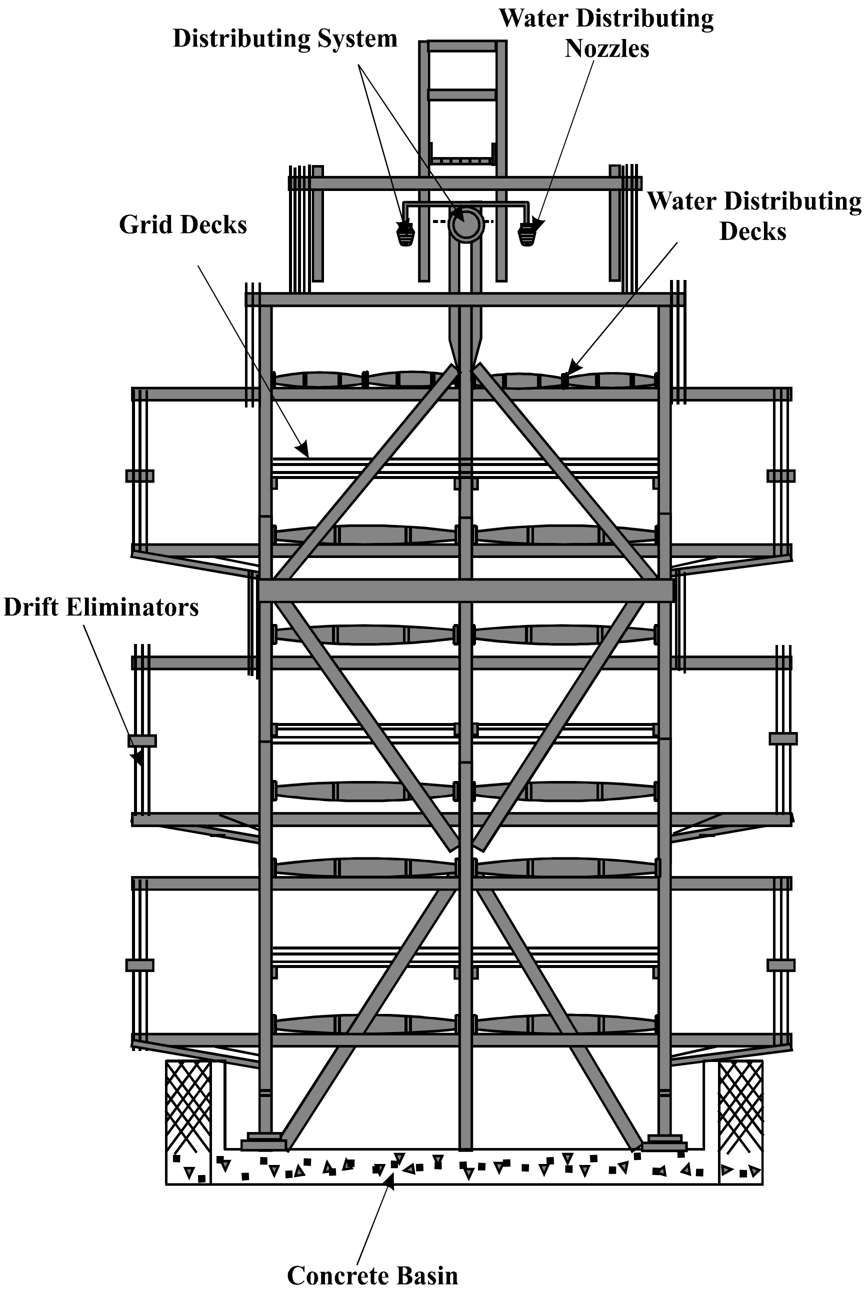


Figure 6.14
Natural-Draf*t* Cooling Tower

Cooling Tower Theory

Heat is transferred from water drops to the surrounding air by the transfer of sensible and latent heat.

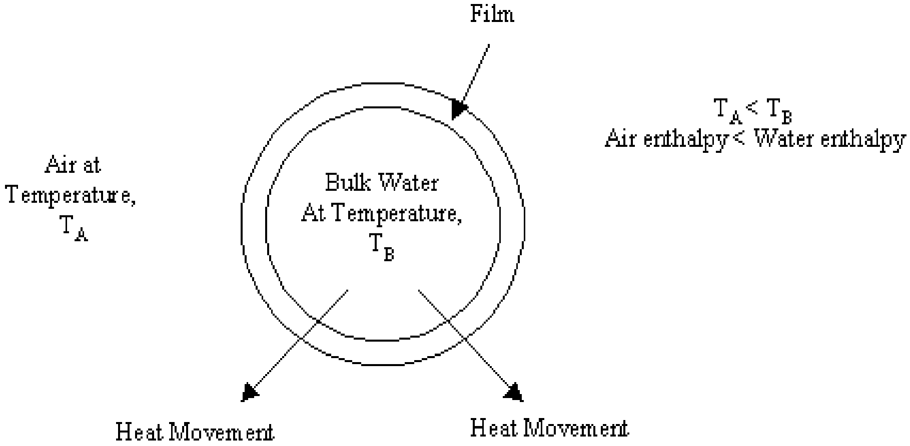
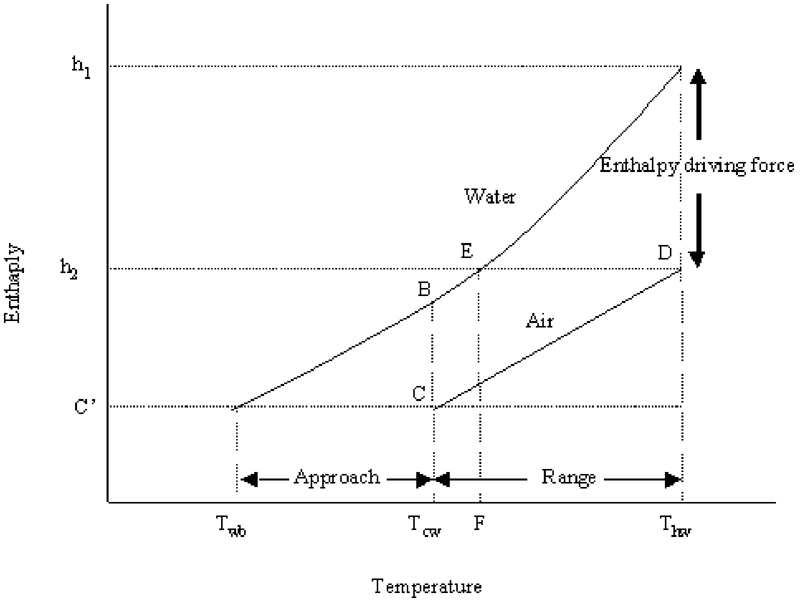


Figure 6.15

Water Drop with Interfacial Film



The following represents a key to Figure

C' = Entering air enthalpy at wet-bulb temperature, T_{wb}

BC = Initial enthalpy driving force

CD = Air operating line with slope L/G

DEF = Projecting the exiting air point onto the water operating line and then onto the temperature axis shows the outlet air web-bulb temperature.

Below is the summary of steps in the cooling tower design process in industry. More detail on these steps will be given later.

1. Plant engineer defines the cooling water flowrate, and the inlet and outlet water temperatures for the tower.

2. Manufacturer designs the tower to be able to meet these criteria on a "worst case scenario" (ie. during the hottest months). The tower characteristic curves and the estimate is given to the plant engineer.

3. Plant engineer reviews bids and makes a selection.

Design Considerations

Once a tower characteristic has been established between the plant engineer and the manufacturer, the manufacturer must design a tower that matches this value. The required tower size will be a function of:

1. Cooling range
2. Approach to wet bulb temperature
3. Mass flowrate of water
4. Web bulb temperature
5. Air velocity through tower or individual tower cell
6. Tower height

Operation Considerations

Water Make-up

Water losses include evaporation, drift (water entrained in discharge vapor), and blowdown (water released to discard solids). Drift losses are estimated to be between 0.1 and 0.2% of water supply.

Evaporation Loss = 0.00085 * water flowrate(T_1-T_2)

Blowdown Loss = Evaporation Loss/(cycles-1)

where cycles is the ratio of solids in the circulating water to the solids in the make-up water

Total Losses = Drift Losses + Evaporation Losses + Blowdown Losses

Cold Weather Operation

Even during cold weather months, the plant engineer should maintain the design water flowrate and heat load in each cell of the cooling tower. If less water is needed due to temperature changes (i.e. the water is colder), one or more cells should be turned off to maintain the design flow in the other cells. The water in the base of the tower should be maintained between 60 and 70 ^{0}F by adjusting air volume if necessary. Usual practice is to run the fans at half speed or turn them off during colder months to maintain this temperature range.

6.5.2 Adiabatic Saturator

When a liquid reaches a definite steady-state temperature, it is called adiabatic-saturation temperature. A typical adiabatic Saturator shown in figure 6.16.

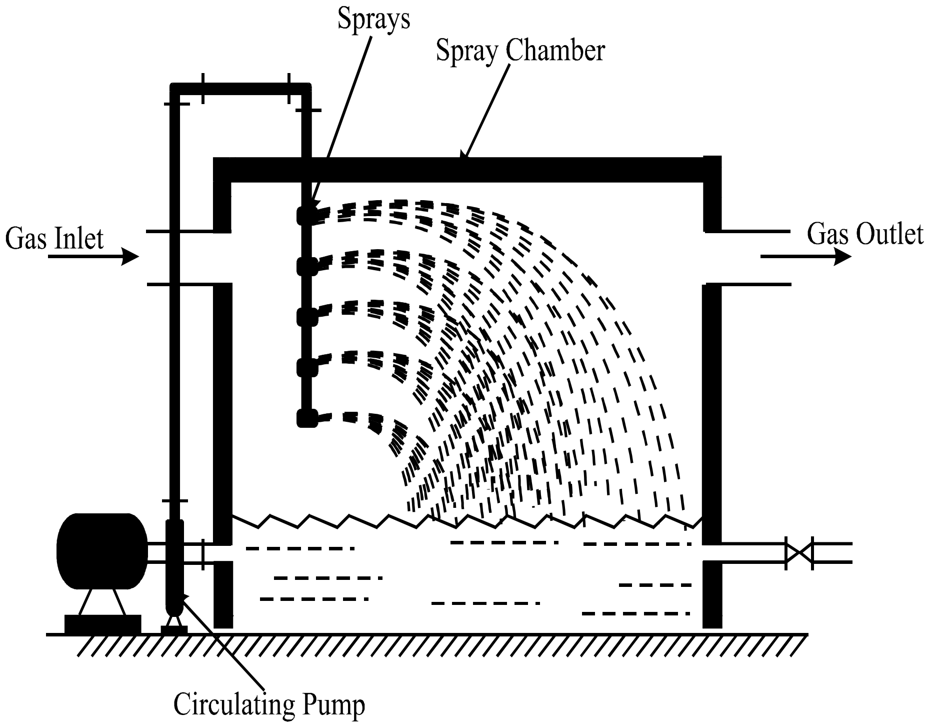


Figure 6.16
Adiabatic Saturator

6.6 Adsorption

Most adsorbent are highly porous materials, and adsorption takes place primarily on the walls of the pores or at specific sites inside the particle. Because the pores are generally very small, the inside of the surface area is greater in magnitude than the external area and may be as large 2,000m^2/g. Separation occurs because differences in molecular weight or polarity cause some molecules to be held more strongly on the surface than others. In many cases, the absorbing component (or adsorbate) is held strongly enough to permit complete removal of that component from the fluid with very little adsorption of other components. Regeneration of the adsorbent can then be carried out to obtain the adsorbate in concentrated or nearly pure form.

6.6.1 Adsorption Equipment

Fixed-bed Adsorbers

A typical equipment system used for adsorption of solvent vapors is shown in Fig. 6.17. The adsorbent particles are placed in a bed 1 to 4ft deep supported on a screen or perforated plate. The feed gas passes down through one of the beds while the other is being regenerated. Downflow is preferred because upflow at high rates might fluidize the particles, causing attrition and loss of fines. When the concentration of solute in the exit gas reaches a certain value, or at a scheduled time, valves are automatically switched to direct the feed to the other bed and initiate the regeneration sequence.

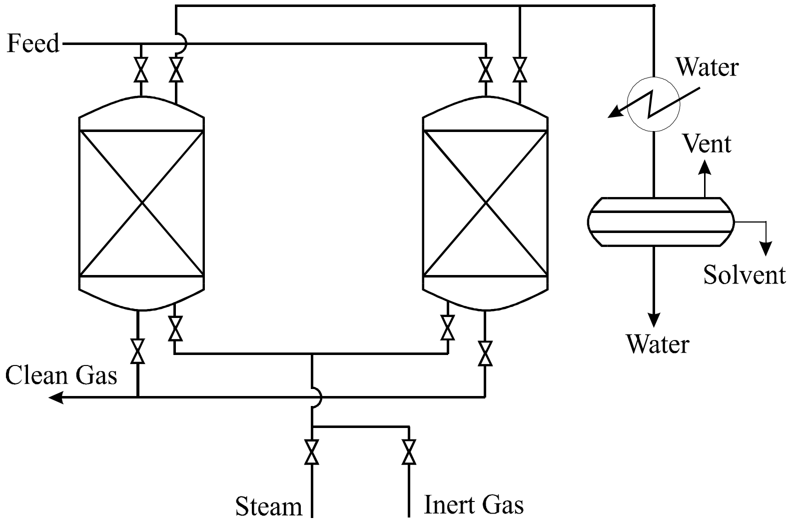


Figure 6.17
Vapor- Phase Adsorption System

Regeneration can be carried out with hot inert gas, but stream is usually preferred if the solve is not miscible with water. Stream condenses in the bed, raising the temperature of the solid and providing the energy for desorption. The solve is condensed, separated from the water, and perhaps dried before re-use. The bed may then be cooled and dried with inert gas, but it is not necessary to lower the entire bed to ambient temperature. If some water vapor can be tolerated in the clean gas, evaporation of water during the adsorption cycle will help cool the bed and partially offset the heat of adsorption.

The size of the adsorbent bed is determined by the gas flow rate and the desired cycle time. Usually the cross-sectional area is calculated to give a superficial velocity of 0.5 to 1.5ft/s (0.15 to 0.45 m/s), which results in a pressure drop of a few inches of water per foot when using typical adsorbents (4 by 10 mesh or 6 by 16 mesh). For very large flow rates, a rectangular bed may be installed in the middle of a horizontal cylinder rather than using a vertical tank with a diameter much greater than the bed depth.

6.7 Drying of Solids

In general, drying a solid means the removal of relatively small amounts of water or other liquid from the solid material, to reduce the content of residual liquid to an acceptably low value. Drying is usually the final step in a series of operations, and the product from a dryer is often ready for final packaging.

6.7.1 Classification of Dryers

There is no simple way of classifying drying equipment. Some dryers are continuous, and some operate batch wise; some agitate the solids, and some are essentially unagitated. Operation under vacuum may be used to reduce the drying temperature. Some dryers can handle almost any kind of material, while others are severely limited in the type of feed they can accept.

A major division may be made between (1) dryers in which the solid is directly exposed to a hot gas (usually air), and (2) dryers in which heat is transferred to the solid from an external medium such as condensing steam, usually through a metal surface with which the solid is in contact. Dryers, which expose the solids to a hot gas, are called adiabatic or direct dryers; those in which heat is transferred from an external medium are known as non-adiabatic or indirect dryers. Dryers heated by dielectric, radiant or microwave energy are also non-adiabatic. Some units combine adiabatic and non-adiabatic drying; they are known as direct-indirect dryers.

6.8 Drying Equipment

6.8.1 Dryers for Solids and Pastes

Typical dryers for solids and pastes include tray and screen-conveyor dryers for materials which cannot be agitated, and tower, rotary, screw-conveyor, fluid-bed, and flash dryers where agitation is permissible. In the following treatment these types are ordered, as far as possible, according to the degree of agitation and the method of exposing the solid to the gas or contacting it with a hot surface, as discussed at the beginning of this chapter. The ordering is complicated, however, by the fact that some types of dryers may be either adiabatic or non-adiabatic, or a combination of both.

6.8.2 Tray Dryers

Tray dryers are useful when the production rate is small. They can dry almost anything, but because of the labor required for loading and unloading, they are expensive to operate. They find most frequent application on valuable products like dyes and pharmaceuticals. Drying by circulation of air across stationary layers of solid is slow, and drying is used, but this is usually neither economical nor necessary in batch dryers because shortening the drying cycle does not reduce the labor required for each batch. A typical tray dryer shown in figure 6.18.

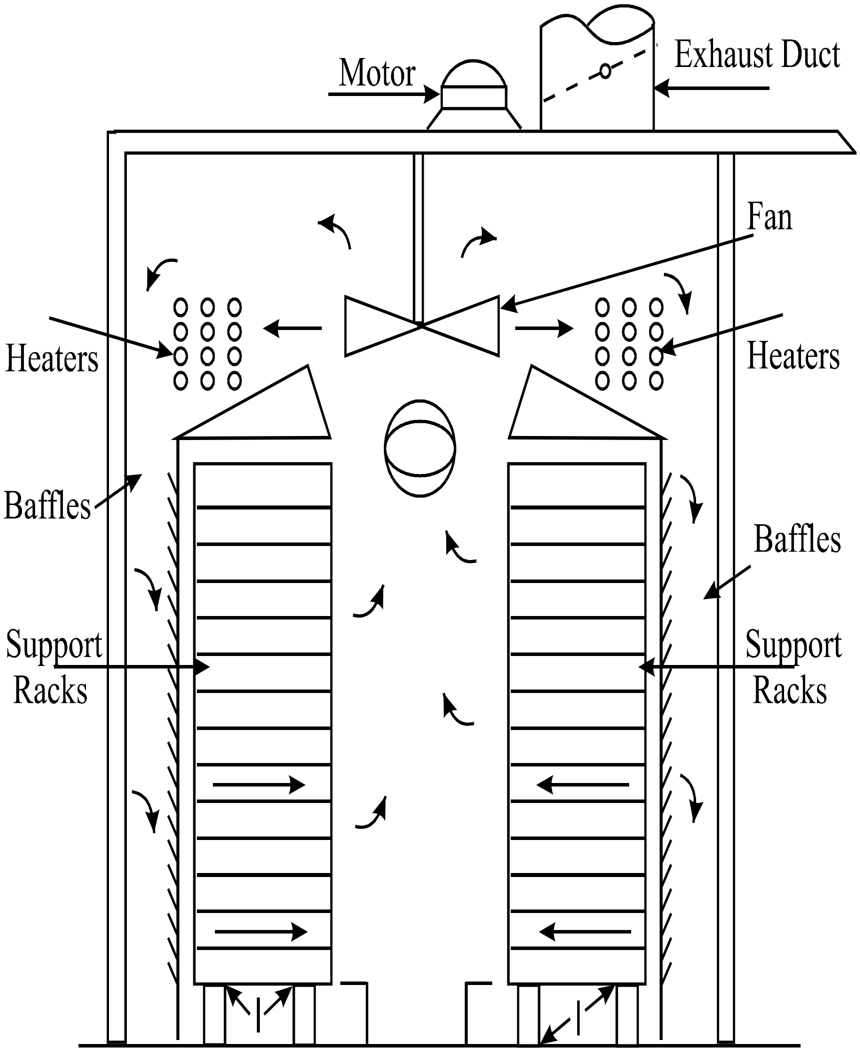


Figure 6.18
Tray Dryer

6.8.3 Screen-Conveyor Dryers

Screen-conveyor dryers handle a variety of solids continuously and with a very gentle action; their cost is reasonable, and their steam consumption is low, typically 21b of steam per pound of water evaporated. Air may be recirculated through, and vented from one section to another counter currently to the solid. These dryers are particularly applicable when the drying conditions must be appreciably changed as the moisture content of the solid is reduced.

6.8.4 Tower Dryers

A tower dryer contains a series of circular trays mounted one above the other on a central rotating shaft. Solid feed dropped on the topmost tray is exposed to a stream of hot air or gas, which passes across the tray. The solid is then scraped off and dropped to the tray below. It travels in this way through the dryer, discharging as dry product from the bottom of the tower. The flow of solids and gas may be either parallel or countercurrent.

6.8.5 Rotary Dryers

A rotary dryer consists of a revolving cylindrical shell, horizontal or slightly inclined toward the outlet. We feed input into one end of the cylinder; dry material discharges from the other. As the shell rotates, internal flights lift the solids and shower them down through the interior of the shell. Rotary dryers are heated by direct contact of gas with the solids, by hot gas passing through an external jacket, or by steam condensing in a set of longitudinal tubes mounted on the inner surface of the shell. The last of these types is called a steam-tube rotary dryer. In a direct-indirect rotary dryer hot gas first passes through the jacket and then through the shell, where it comes into contact with the solids.

6.8.6 Screw-Conveyor Dryers

A screw-conveyor dryer is a continuous indirect-heat dryer, consisting essentially of a horizontal screw conveyor (or paddle conveyor) enclosed in a cylindrical jacketed shell. Solid fed in one end is conveyed slowly through the heated zone and discharges from the other end. The vapor evolved is withdrawn through pipes set in the roof of the shell. The shell is 3 to 24 in. (75 to 600mm) in diameter and up to 20ft (6m) along; when more length is required, several conveyors are set one above another. Coolant in the jacket lowers the temperature of the dried solids before they are discharged.

The rate of rotation of the conveyor is slow, from 2 to 30 r/min. Heat-transfer coefficients are based on the entire inner surface of the shell, even though the shell runs only 10 to 60 percent full. The coefficient depends on the loading in the shell and on the conveyor speed. It ranges, for many solids, between 3 and 10 Btu/ft^2-h-^{o}F (17 and 57 W/m^2-^{o}C).

Screw-conveyor dryers handle solids that are too fine and too sticky for rotary dryers. They are completely enclosed and permit recovery of solvent vapors with little or no dilution by air. When provided with appropriate feeders, they can be operated under moderate vacuum. Thus they are adaptable to the continuous removal and recovery of volatile solvents from solvent-wet solids, such as spent meal from leaching operations. For this reason they are sometimes known as desolventizers.

6.8.7 Fluid-Bed Dryers

Dryers in which the solids are fluidized by the drying gas find applications in a variety of drying problems. The particles are fluidized by air or gas in a boiling-bed unit. Mixing and heat transfer are very rapid. Wet feed is admitted to the top of the bed; dry product is taken out from the side, near the bottom. In the dryer shown in Fig. 6.19 there is a random distribution of residence times; the average time a particle stays in the dryer is typically 30 to 120 s when only surface liquid is vaporized, and up to 15 to 30 min if there is also internal diffusion.

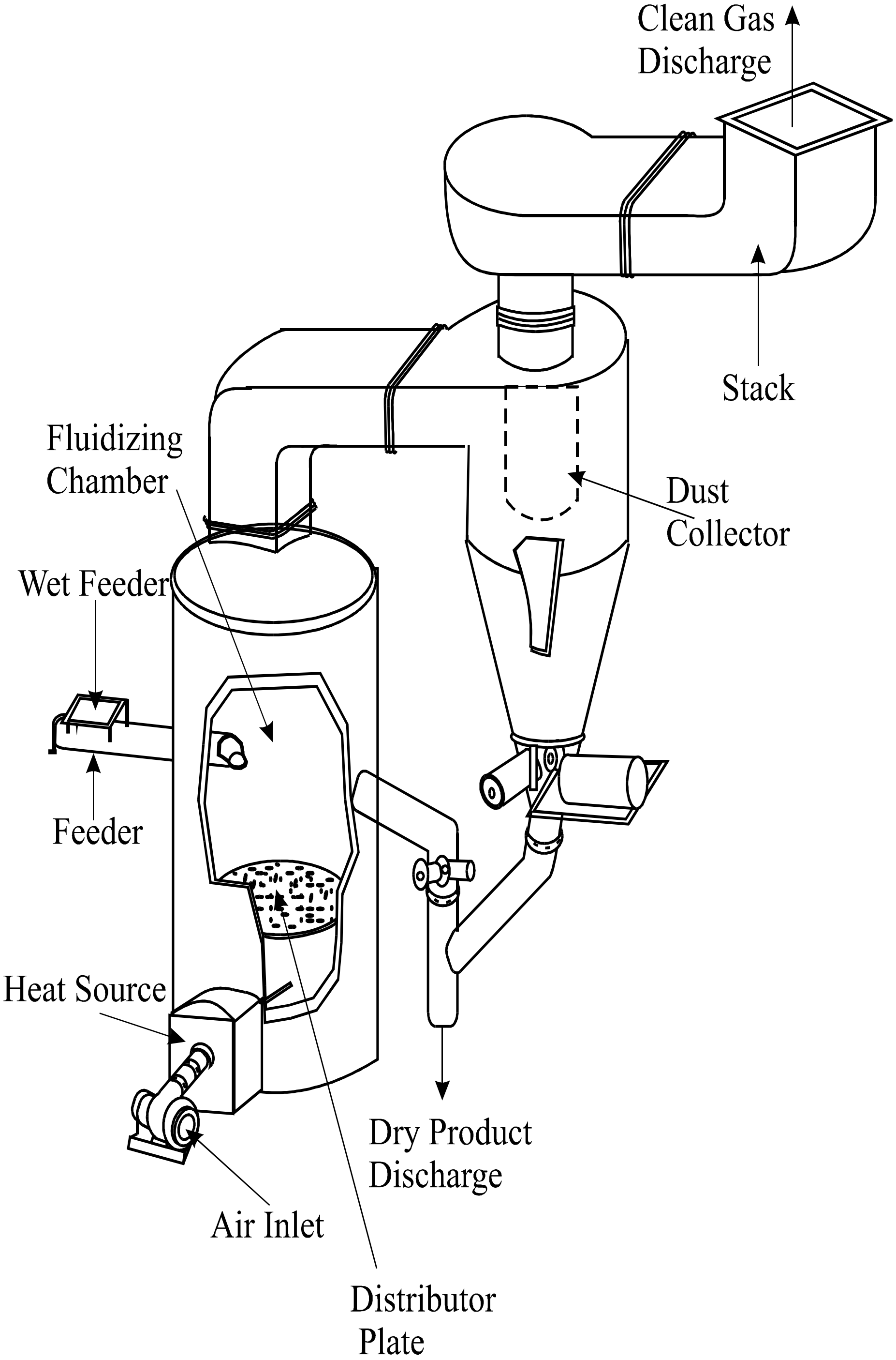


Figure 6.19
Continuous Fluid-Bed Dryer

Small particles are heated essentially to the exit dry-bulb temperature of the fluidizing gas; consequently, thermally sensitive materials must be dried in a relatively cool suspending medium. Even so, the inlet gas may be hot, for it mixes so rapidly that the temperature is virtually uniform, at the exit gas temperature, throughout the bed. If fine particles are present, either from the feed or from particle breakage in the fluidized bed, there may be considerable solids carry-over with the exit gas and cyclones and bag filters are needed for fines recovery.

Some rectangular fluid-bed dryers have separately fluidized compartments through which the solids move in sequence from inlet to outlet. These are known as "plug-flow dryers"; in them the residence time is almost the same for all particles. Dryers' conditions can be changed from one compartment to another, and often the last compartment is fluidized with cold gas to cool the solids before discharge.

6.8.8 Flash Dryers

In a flash dryer, a wet pulverized solid is transported for a few seconds in a hot gas stream. Drying takes place during transportation. The rate of heat transfer from the gas to the suspended solid particles is high, and drying is rapid, so that no more than 3 or 4 s is required to evaporate substantially all the moisture from the solid. The temperature of the gas is high - often about 1200^{o}F at the inlet - but the time of contact is so short that the temperature of the solid rarely rises more than 100^{o}F during drying. Flash drying may therefore be applied to sensitive materials that in other dryers would have to be dried indirectly by a much cooler heating medium.

6.9 Dryers for Solutions and Slurries

6.9.1 Spray Dryers

In a spray dryer, a slurry or liquid solution is dispersed into a stream of hot gas in the form of a mist of fine droplets. Moisture is rapidly vaporized from the droplets, leaving residual particles of dry solid, which are then separated from the gas stream. The flow of liquid and gas may be co-current, countercurrent, or a combination of both in the same unit.

6.9.2 Thin-Film Dryers

Competitive with spray dryers in some situations, are thin-film dryers, which can accept a liquid, or a slurry feed and produce a dry, free-flowing solid product. Here most of the liquid is removed from the feed, and partially wet solid is discharged to the second section, in which the residual liquid content of the material from the first section is reduced to the desired value.

6.9.3 Drum Dryers

A drum dryer consists of one or more heated metal rolls on the outside of which a thin layer of liquid is evaporated to dryness. Dried solid is scraped off the rolls as they slowly revolve.