جزوه زبان تخصصی

استاد: ادراکی

Introduction to Chemical Engineering

Introduction

The **profession** of chemical engineering has to do with the technology of the chemical and process industries. This group of industries is not easy to define. It is not restricted to those in which a chemical change is performed on the material being treated.for instance the **manufacture** of salt, which is always considered in the group of chemical industries, can conceivably be carried out so that not a single chemical reaction occurs. The term "chemical and process industries" is simply one that has a certain accepted **usage**.

Chemical engineering is both an art and a science. Parts of it are quite thoroughly understood theoretically. In these areas, chemical engineering is a science. Many other field of chemical engineering is only partly understood theoretically, although here the theory that is available is always a **valuable** guide to practice. Still other areas have not responded to theoretical analysis at all and remain an art. Chemical engineering is not **unique** in this respect; and all engineering for many years to come, **irrespective** of the amount of research that will be done, will remain to a certain extent an art, i.e., the doing of things on the basis of experience and judgment. Several subdivisions of the work of the chemical engineer are recognized, and the divisions between some of these are rather **arbitrary**.

The Unit Operation of Chemical Engineering

The earliest successful effort to bring some kind of system into a study of the process industries came from the recognition that many of these processes had common operations and common techniques and were based on the same foundation of **scientific principles**. For instance, in almost all of them there is a flow of heat between hot and cold fluids. There is transportation of materials, both liquid and solid, on a large scale. Many different processes utilize the same separation or **purification** steps, such as distillation, extraction, filtration, and absorption.

The concept of the 'unit operation' was a final crystallize of these ideas into a **formal point of view**. It emphasized the fact that an industrial process contains a **coordinated** series of separate operations and that the best method of analyzing and understanding a process is to analyze and understand these operations themselves. The unit operations are thus independent of the industries in which they are used, except that practical methods of carrying them out may be more or less different in different industries. The **concept** of unit operations, however, has greatly unified much of the subject matter of chemical engineering.

The theory of the unit operations is based on **fairly** definite, well understood laws. However, this theory must in turn be **interpreted** into terms of practical equipment that can be **fabricated, assembled**, operated, and maintained. The chemical engineer must be able to develop, design, and engineer both process and equipment. He must be able to operate plant efficiently, safely, and economically, and he must understand the use that will be made of his products so that he can make a product having the particular characteristics demanded by the **purchaser**. Consequently, there is much that is practical in chemical engineering, in addition to its theoretical background. Balanced treatment of each of the unit operation requires that both theory and practice be given an equal consideration.

Material Balance

The first fundamental law states that matter cannot be either created or destroyed. Specifically, this requires that the materials entering any process must either **accumulate** or leave the process. There can be no loss or gain during the process. In **steady-state** conditions (conditions which do not very with time), **the law of conservation of matter** takes the extremely simple form that input must equal output. The law is often used in the form of material balances. The importance of this simple but far-reaching statement can hardly be over emphasized. Material balances must hold over the **entire** process or apparatus or over any part of it. They must apply to all the material that enters and leaves the process or to any one material that passes through the process unchanged.

Molecular Units

In material-balance calculations where chemical reactions are involved, molecular units are often simpler to use than the ordinary units of weight. A mole of any pure substance is defined as that quantity whose weight is **numerically** equal to its molecular weight. From this definition, the meanings of the terms pound mole and gram mole follow.

Fluid Mechanics

Fluids

In everyday life, we recognize three states of matter: solid, liquid and gas. Although different in many respects, liquids and gases have a common characteristic in which they differ from solids; they are fluids, **lacking** the ability of solids to offer permanent resistance to a deforming force. Fluids flow under the action of such forces, deforming continuously for as long as the force is applied. A fluid is unable to **retain** unsupported shape; it flows under its own weight and takes the shape of any solid body with which it comes into contact.

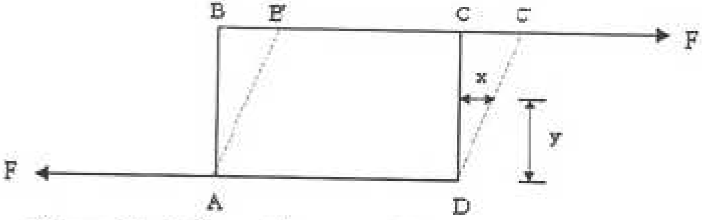


Figure 2-1. Deformation caused by shearing forces.

Deformation is caused by **shearing** forces, i.e. forces such as F (Figure 2-1), which act **tangentially** to the surfaces to which they are applied and cause the material originally occupying the space ABCD to deform to AB′C′D. This leads to the definition:

A fluid is a substance which deforms continuously under the action of shearing forces, however small they may be. Conversely, it follows that:

If a fluid is at rest there can be no shearing forces acting and, therefore, all forces in the fluid must be **perpendicular** to the planes upon which they act.

Newtonian Fluids

Even among substances commonly accepted as fluids, there is wide variation in behavior under stress. Fluids obeying Newton's law of viscosity (equation 1) and for which μ has a constant value are known as Newtonian fluids. Most common fluids **fall into** this category, for which shear stress is linearly related to velocity gradient.

$$\tau = \mu \frac{du}{dy} \qquad (1)$$

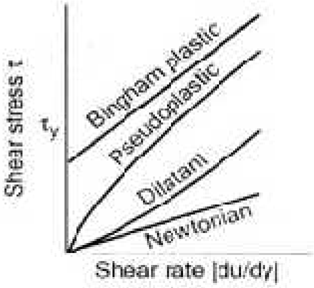
Non-Newtonian Fluids

Fluids which do not obey Newton's law of viscosity are known as non-Newtonian and fall into one of the following groups.

(i) Plastic, for which the shear stress must reach a certain minimum value before flow **commences**. Thereafter, shear stress increases with the rate of shear according to the relationship.

$$\tau = A + B\left(\frac{du}{dy}\right)^n \qquad (2)$$

where A, B and n are constants. If $n = 1$, the material is known as a Bingham plastic (e.g. **sewage sludge**).



(ii) Pseudo-plastic, for which dynamic viscosity decreases as the rate of shear increases (e.g. colloidal solutions, clay, milk, cement).

(iii) Dilatant substances, in which dynamic viscosity increases as the rate of shear increases (e.g. quicksand).

(iv) Thixotropic substances, for which the dynamic viscosity decreases with the time for which shearing forces are applied (e.g. thixotropic jelly paints).

(v) Rheopectic materials, for which the dynamic viscosity increases with the time for which shearing forces are applied.

(vi) Viscoelastic materials, which behave in a manner similar to Newtonian fluids under time-invariant conditions but, if the shear stress changes suddenly, behave as if plastic.

The above is a classification of actual fluids. In analyzing some of the problems arising in fluid mechanics we shall have cause to consider the behavior of an ideal fluid, which is assumed to have no viscosity. Theoretical solutions obtained for such a fluid often give valuable **insight** into the problems involved and where necessary, can be related to real conditions by experimental investigation.

Uniform and non-uniform Flow

Conditions in a body of fluid can vary from point to point and, at any given point, can vary from one moment of time to the next. Flow is described as uniform if the velocity at a given instant is the same in **magnitude** and **direction** at every point in the fluid. If velocity changes from point to point at the given instant, the flow is described as non-uniform. In practice, when a fluid flows past a solid boundary, there will be variations of velocity in the region close to the boundary However, if the size and shape of the **cross-section** of the stream of fluid is constant, the flow is considered to be uniform.

Steady and unsteady Flow

A steady flow is one in which the velocity, pressure and cross-section of the stream may vary from point to point but do not change with time. If, at a given point, conditions do change with time, the flow is described as unsteady. In practice, there will always be **slight** variations of velocity and pressure, but, if the average values are constant, the flow is considered to be steady.

There are, therefore, four possible types of flow:

(i) Steady uniform flow. Conditions do not change with position or time. The velocity and cross-sectional area of the stream of fluid are the same at each cross-section; e.g. flow of a liquid through a pipe of uniform bore running completely full at constant velocity.

(ii) Steady non-uniform flow. Conditions change from point to point but not with time. The velocity and cross-sectional area of the stream may vary from cross-section to cross-section, but, for each cross-section, they will not vary with time; e.g. flow of a liquid at a constant rate through a **tapering pipe** running completely full.

(iii) Unsteady uniform flow. At a given instant of time, the velocity at every point is the same, but this velocity will change with time; e.g. accelerating flow of a liquid through a pipe of uniform bore running full, such as would occur when a pump is **started up**.

(iv) Unsteady non-uniform flow. The cross-sectional area and velocity vary from point to point and also change with time; e.g. a wave traveling along a channel.

Compressible and Incompressible Flow

All fluids are compressible so that their density will change with pressure. but under steady flow conditions and provided that the changes of density are small it is often possible to simplify the analysis of a problem by assuming that the fluid is incompressible and constant density. Since liquids are relatively difficult to compress, it is usual to treat them as if they were incompressible for all cases of steady flow. However, in unsteady flow conditions, high pressure differences can develop and the **compressibility** of liquid must be taken into account. Gases are easily compressed and, except when changes of pressure and, therefore, density are very small, the effects of compressibility and changes of internal energy must be taken into account.

Laminar Flow

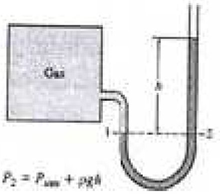
Observation shows that two entirely different types of fluid flow exist. This was demonstrated by Osborne Reynolds in 1883 through an experiment in which water was **discharged** from a tank through a glass tube. The rate of flow could be controlled by a valve at the outlet, and a fine filament of dye injected at the entrance to the tube. At low velocities, it was found that the dye filament remained intact throughout the length of the tube, showing that the particles of water moved in parallel lines. This type of flow is known as laminar, viscous or streamline, the particles of fluid moving in an orderly manner and retaining the same relative positions in **successive** cross-sections.

Turbulent Flow

As the velocity in the tube was increased by opening the outlet valve, a point was eventually reached at which the dye **filament** at first began to **oscillate** and then broke up so that the color was diffused over the whole cross-sections, showing that the particles of fluid no longer moved in an orderly manner but occupied different relative positions in successive cross-sections. This type of flow is known as turbulent and is characterized by continuous small **fluctuations** in the magnitude and direction of the velocity of the fluid particles, which are accompanied by corresponding small fluctuations of pressure.

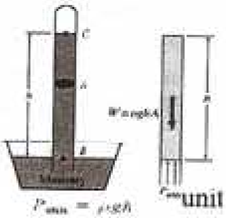
Manometer

Manometer is commonly used to measure small and moderate pressure differences. A manometer mainly consists of a glass or plastic U-tube containing one or more fluids such as mercury, water, alcohol, or oil. To keep the size of the manometer to a manageable level, heavy fluids such as mercury are used if large pressure differences are anticipated. The diameter of the tube should be large enough (more than a few millimeters) to ensure that the surface **tension** effect and thus the capillary rise is negligible.



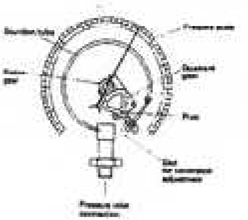
Barometer

Atmospheric pressure is measured by a device called a barometer; thus, the atmospheric pressure is often referred to as the *barometric pressure*. The Italian Torricelli (1608–1647) was the first to conclusively prove that the atmospheric pressure can be measured by **inverting** a mercury-filled tube into a mercury container that is open to the atmosphere. The standard atmospheric pressure, for example, is 760 mmHg (29.92 inHg) at 0°C. The mmHg is also called the torr in **honor** of Torricelli.

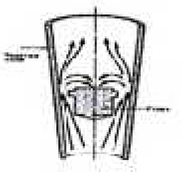


The Bourdon gauge

This gauge is widely used for steam and compressed gases, and frequently forms the indicating element on flow controllers. This instrument has a very much greater **sensitivity** and is suitable for very high pressures. The pressure indicated is the difference between that communicated by the system to the tube and the external (ambient) pressure, and this is usually referred to as the *gauge* pressure. It is then necessary to add on the ambient pressure in order to obtain the (absolute) pressure.

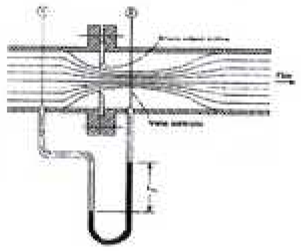


Rotameter



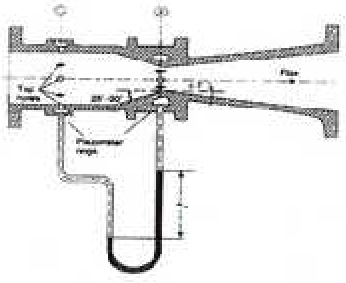
In the rotameter, the pressure drop is held constant and the constriction area varies as the flow rate changes. A **float** is free to move up and down in a tapered tube. The float remains steady when the upward force of the flowing fluid exactly balances the weight of the float in the fluid. As the fluid flow rate is increased, the float moves to a higher position in the tube.

The orifice meter



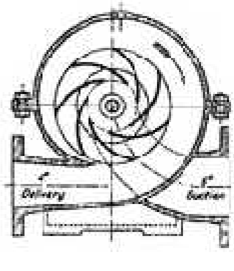
This is a relatively cheap and **reliable** instrument though the overall pressure drop is high because most of the kinetic energy of the fluid at the orifice is wasted. The velocity of the fluid is increased at the **throat** without much loss of energy. The most important factors influencing the reading of an orifice meter are the size of the orifice and the diameter of the pipe in which it is fitted. The orifice must be drilled with sharp edges and is best made from stainless steel which resists **corrosion** and **abrasion.** The size of the orifice should be chosen to give a convenient pressure drop.

The venturi meter



In this meter, the fluid is accelerated by its passage through a converging **cone** of angle 15-20°. The fluid is then retarded in a cone of smaller angle (5-7°) in which a large proportion of the kinetic energy is converted back to pressure energy. The pressure difference between the **upstream** end of the cone (section 1) and the throat (section 2) is measured. The attraction of this meter lies in its high energy recovery so that it may be used where only a small pressure head is available, though its construction is expensive.

Pump



Pumps are of two main classes: centrifugal and the others. These others mostly have **positive displacement** action in which the discharge rate is largely independent of the pressure against which they work. **Centrifugal** pumps have rotating elements that impart high velocity initially and high pressure head ultimately to the liquid. *Pumps* work very much like compressers except that they handle liquids instead of gases. Centrifugal pumps have a number of good qualities: (1) They are simple in construction, are inexpensive, are available in a large variety of materials, and have low maintenance cost. (2) They operate at high speed so that they can be driven directly by electrical motors.

Thermodynamics

Thermodynamic Systems

A thermodynamic system is defined as any quantity of matter or any region of space to which attention is directed for purposes of analysis. The quantity of matter or region of space must be within a prescribed **boundary**. This boundary may be deformable and may be **imaginary**.

If a system is defined as a particular quantity of matter, then the system always contains the same matter and there can be no transfer of mass across the boundary. However, if a system is defined as a region of space within a prescribed boundary, then matter may cross the system boundary.

In order to **distinguish** between these two types of systems, the type that has no mass transfer across its boundary we call a closed system or control mass. An open system is a region of space within a boundary which matter may cross. This boundary may be moving. An open system is also called a control volume and its boundary is called a control surface.

Everything outside the system boundary is referred to as the surroundings. Usually the term surroundings is restricted to those things outside the system that is some way **interact** with the system or affect the behavior of the system. A special case of a closed system is an **isolated** system. An isolated system is a system that in no way interacts with its surroundings. Notice that an isolated system must be a closed system, since the requirement that there be no interaction of the system with its surroundings prohibits any transfer of mass across the system boundary.

Properties, States, and Processes

Properties

A property is any observable characteristic of a system. Examples of properties are pressure, temperature, modulus of **elasticity**, volume, and dynamic viscosity. We also consider as properties any combination of observable characteristics, for example, the product of pressure and temperature.

States

The state or condition of a system is specified by the values of its properties. Since there are **numerous** relationships among the properties of particular systems, the values of a few properties will often identify a state completely because all other properties can be determined in terms of these few. Precisely how many properties are required to specify the state of a system depends on the **complexity** of the system.

If a system has the same values of its properties at two different times, the system is in identical states at these two times. A system is said to be in an equilibrium state (or in equilibrium) if no changes can occur in the state of the system without the aid of an external **stimulus**.

Processes

A transformation of a system from one state to another is called a process. The path of the process is the series of states through which the system passes during the process. A cycle or **cyclic** process is a process (or a series of processes) which returns the system to the state it was in before the process began. The properties of the system vary during a cycle, but at the completion of a cycle all properties have been restored to their initial values. In other words, the net change in a property is zero for any cycle. This is concisely stated by $\oint dx = 0$

Where x is any property and the symbol $\oint$ indicates integration around a cycle.

Intensive, Extensive, and Specific Properties

If a **homogeneous** system is divided into two parts, the mass of the whole system is equal to the sum of the masses of the two parts. The volume of the whole is also equal to the sum of the volumes of the parts. On the other hand, the temperature of the whole is not equal to the sum of the temperatures of the parts. In fact, the temperature, pressure, and density of the whole are the same as of the parts. This brings us to the **distinction** between extensive and intensive properties.

If the value of a property of a system is equal to the sum of the values for the parts of the system, that property is an extensive property. Mass, volume, weight, and several other properties (energy, enthalpy, entropy) are extensive properties. An intensive property is one which has the same value for any part of a homogeneous system as it does for the whole system. The measurement of an intensive property can be made without knowledge of the total mass or extent of the system. Pressure, temperature, and density are examples of intensive properties. If the value of any extensive property is divided by the mass of the system, the resulting property is intensive and is called a specific property.

The First Law of Thermodynamics

An empirical relationship between heat and work has been found. As a result of this relationship, stored energy can be operationally defined as "$\Delta E = Q - W$" Where ΔE is the change in the stored energy of a closed system, Q is the net amount of heat added to the system, and W is the net amount of work done by the system. Also it can be shown that stored energy E is a property.

These facts are generally summarized in a statement of the first law of thermodynamics or the law of **conservation** of energy. Possible statements are the following:

1- Whenever a closed system **executes** a cycle, the net amount of heat added to the system during the cycle is equal to the net amount of work done by the system, or $\oint \partial Q = \oint \partial W$.

2- Energy can be neither created nor destroyed, although it can be stored in various forms and can be transferred from one system to another as heat or work.

The Second Law of Thermodynamics

Two of the well-known statements of the second law of thermodynamics are known as the Clausius statement and the Kelvin-Planck statement. The Clausisus statement may be given as follows: It is impossible for any device to operate in such a manner that it produces no effect other than the transfer of heat from one body to another body at a higher temperature. It does not say that it is impossible to transfer heat from a lower-temperature body to a higher-temperature body. Indeed, this is exactly what a **refrigerator** does. A refrigerator does not operate, unless it receives an energy input, usually in the form of work.

The Kelvin-Planck statement of the second law is as follows it is impossible for any device to operate in a cycle and produce work while exchanging heat only with bodies at a single fixed temperature. Notice that the value of the temperature of the bodies in the surroundings is not mentioned. If a device can operate cyclically and produce work while exchanging heat only with bodies at $500°C$, it can be made to do the same thing while exchanging heat only with bodies at, say, $0°C$. Application of the first law to a device which **violates** the Kevin-Planck statement of the second law (recalling that $\oint dE = 0$) shows that the network produced would be equal to the net amount of heat received from bodies in the surroundings which are all at the same temperature. Such a device is called a **perpetual**-motion machine of the second kind. Therefore, the Kelvin-Planck statement is sometimes paraphrased as "A perpetual-motion machine of the second kind is impossible."

The Third Law of Thermodynamics

This law is concerned with the level of availability of energy. It is suggested that the internal energy of a substance results from the random motion of the atoms and molecules which make up the substance. This motion is also associated with temperature and from this develops the idea of an absolute zero of temperature when all random motion **ceases**. Entropy is associated with temperature and with the availability of thermal energy.

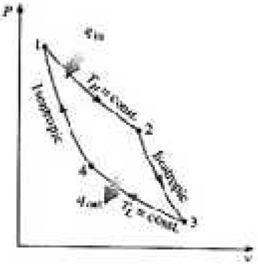
For a substance, if the random **translational**, **rotational** and **vibrational** types of motion of the atoms and molecules making up the substance are reduced to zero, then the substance is considered to become of a perfect crystal form and the energies associated with these form of motion will be reduced to zero. Thus, the energy within the substance is reduced to what is referred to as the ground state. This neglects the energy within the basic atomic structure of the substance which is associated with such particles as electrons, neutrons, etc. These considerations led to the development of the third law of thermodynamics, which is the concept that at the absolute zero of temperature, the energy of a perfect crystal of a substance is zero.

Enthalpy

It is known that internal energy, pressure and volume are properties. Usually a particular combination of these properties will often appear. The combination is in the form $u + Pv$ and because this combination has a particular **significance** in some processes, it is given a name. The name is enthalpy and is given the symbol h. Thus, $h = u + Pv$. Note that, since pressure, volume and temperature are properties, the combination of these properties in the form of enthalpy makes enthalpy a property also. Specific enthalpy is designated h. The enthalpy of any mass, other than unity is designated H.

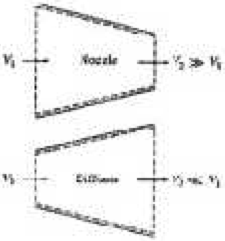
Carnot cycle

The Carnot cycle is composed of four totally reversible processes: isothermal **expansion**, adiabatic expansion, isothermal compression, and adiabatic compression. The Carnot cycle can be executed in a closed system (a piston–cylinder device) or a steady-flow system (utilizing two turbines and two compressors), and either a gas or a vapor can be utilized as the working fluid. The Carnot cycle is the most efficient cycle that can be executed between a heat source at temperature T_H and a sink at temperature T_L, and its thermal efficiency is expressed as $\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$



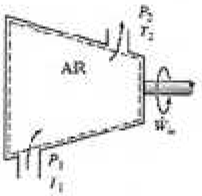
Nozzles and diffusers

Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses. A nozzle is a device that *increases the velocity of a fluid* at the expense of pressure. A diffuser is a device that *increases the pressure of a fluid* by slowing it down. That is, nozzles and diffusers perform opposite tasks. The cross-sectional area of a nozzle decreases in the flow direction for **subsonic** flows and increases for **supersonic** flows. The reverse is true for diffusers. Nozzles and diffusers typically involve no work and any change in potential energy is negligible $(\Delta Pe \cong 0)$.



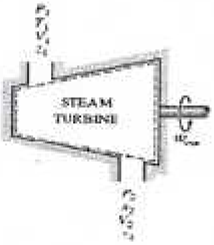
Compressor

Compressors are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft. Therefore, compressors involve work inputs. A *compressor* is capable of compressing the gas to very high pressures. Heat transfer is **negligible** for compressors unless there is intentional cooling. The several kinds of commercial compressors are identified in this classification: (1) Rotodynamic: a. Centrifugal (radial flow) b. **Axial** flow; (2) Positive displacement: a. **Reciprocating** piston b. Rotary (screws, blades, lobes, etc.).



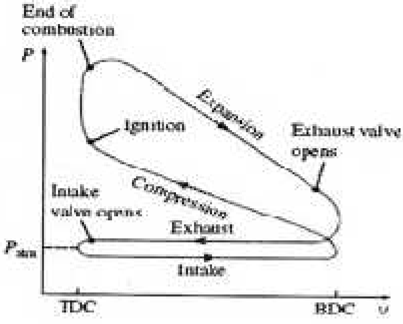
Turbine

In steam, gas, or hydroelectric power plants, the device that drives the electric generator is the turbine. As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft. As a result, the shaft rotates, and the turbine produces work. Heat transfer from turbines is usually negligible since they are typically well insulated. Potential energy changes are also negligible for turbines. The fluid velocities encountered in most turbines are very high, and the fluid experiences a significant change in its kinetic energy. However, this change is usually very small relative to the change in enthalpy, and thus it is often **disregarded**.

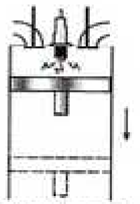


Otto engine

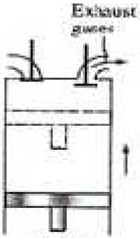
The Otto cycle is the ideal cycle for spark-ignition reciprocating engines. In most spark-ignition engines, the piston executes four complete strokes (two mechanical cycles) within the cylinder, and the crankshaft completes two revolutions for each thermodynamic cycle. These engines are called four-stroke internal combustion engines.



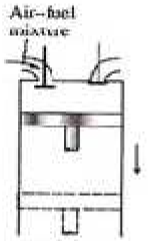
Compression stroke



Power (expansion) stroke



Exhaust stroke

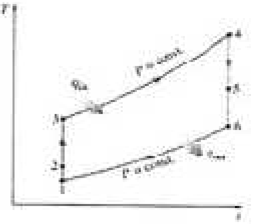


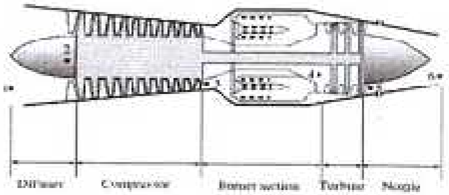
Intake stroke

Initially, both the intake and the exhaust valves are closed, and the piston is at its lowest position (BDC). During the *compression stroke,* the piston moves upward, compressing the air–fuel mixture. Shortly before the piston reaches its highest position (TDC), the spark plug fires and the mixture ignite, increasing the pressure and temperature of the system. The high-pressure gases force the piston down, which in turn forces the crankshaft to rotate, producing a useful work output during the *expansion stroke.* At the end of this stroke, the piston is at its lowest position (the completion of the first mechanical cycle), and the cylinder is filled with combustion products. Now the piston moves upward one more time, **purging** the exhaust gases through the exhaust valve (the *exhaust stroke*), and down a second time, drawing in fresh air–fuel mixture through the intake valve (the *intake stroke*). Notice that the pressure in the cylinder is slightly above the atmospheric value during the exhaust stroke and slightly below during the intake stroke.

Jet engines

The pressure of air rises slightly as it is decelerated in the diffuser. Air is compressed by the compressor. It is mixed with fuel in the combustion chamber, where the mixture is burned at constant pressure. The high-pressure and high-temperature combustion gases partially expand in the turbine, producing enough power to drive the compressor and other equipment. Finally, the gases expand in a nozzle to the ambient pressure and leave the engine at a high velocity. The **thrust** developed in a turbojet engine is the unbalanced force that is caused by the difference in the momentum of the low-velocity air entering the engine and the high-velocity exhaust gases leaving the engine, and it is determined from Newton's second law.





HEAT TRANSFER

Introduction

Heat transfer is the science that **seeks** to predict the energy transfer that may take place between material bodies as a result of a temperature difference. Heat is transferred by three basic modes. In two of these modes, the heat is transferred through material, whereas in the third mode it is transmitted through empty space and vacuum as well as through certain materials **transparent** to thermal radiation. The physical mechanisms and laws for the heat transfer are different for each of these basic modes, which are designated as:

1) Conduction, 2) Convection, 3) Radiation

Conduction

When a temperature gradient exists in a body, experience has shown that there is an energy transfer from the high-temperature region to the low-temperature region. We say that the energy is transferred by conduction.

The mechanism of thermal conduction in a gas is a simple one. We identify the kinetic energy of a molecule with its temperature; thus in a high-temperature region, the molecules have higher velocities than in some lower-temperature region. The molecules are in continuous random motion, colliding with one another and exchanging energy and momentum. The molecules have this random motion whether or not a temperature gradient exists in the gas. The physical mechanism of thermal energy conduction in liquids is **qualitatively** the same as in gases; however, the situation is considerably more complex because the molecules are more closely spaced and molecular force fields exert a strong influence on the energy exchange in the collision process. On the other hand, thermal energy may be conducted in solid by two modes: **Lattice** vibration and transport by free electrons.

Convection

In convection heat flow, the thermal energy is primarily transmitted through **appreciable** displacement (physical circulation of the molecules within the convective body). Convection occurs only in fluids (liquids or gases), and convective heat transfer is usually between a solid surface and a fluid. The fluid molecules in contact with the solid surface are heated or cooled by conduction, and are swept away from the solid surface by convective flow patterns or flow turbulence, and subsequent thermal energy transfer by conduction with **adjacent** fluid molecules occurs. Or conversely, molecules at the temperature of the fluid body are swept toward a solid surface and upon physical contact thermal energy transfer is effected. An example of heat transferred by convection is the **chilling** effect of a cold wind on a warm body. Without the flow of cold air past a warm body, the primary mode of energy transfer would be conduction, which would be much less.

If a heated plate were exposed to ambient room air without an external source of motion, a movement of the air would be experienced as a result of the density gradients near the plate. We call this natural, or free, convection as opposed to forced convection, which is experienced in the case of the fan blowing air over a plate. Boiling and condensation phenomena are also grouped under the general subject of convection heat transfer.

Radiation

In radiation heat transfer, the thermal energy is transmitted by electromagnetic waves, differing from light (visible spectrum) only by their respective wavelengths. These electromagnetic waves (radiant energy) pass readily through vacuum and empty space, and can pass through gases, liquids, and some solids. The emitted radiant energy is not a continuous variable, but is formed by finite batches (or 'quanta') of energy associated with step changes in the energy level of the emitting molecule of the body. The rate of this radiant energy **emission**, and, hence, the rate of radiant that transfer, is proportional to the fourth power of the absolute temperature. This is in contrast to the direct proportionality of conductive and convective heat transfer to the temperature difference or temperature gradient. The transmitted radiant energy is absorbed to varying extents on the surface of bodies upon which it **impinges**, depending upon the **absorptivity** of the body. Sunshine is a common example of radiant heat transfer. The radiant energy of the sun is transmitted through space, and the earth's atmosphere. This transmitted energy is absorbed according to the characteristics of the surface upon which it is incident. Dark clothing usually absorbs a major portion of this radiant energy.

Low Temperature Insulation

Low temperature insulating materials (below -45°C) are used to minimize heat flow into low temperature systems. **Vacuum jackets** with radiation shields are used a great deal for low temperature insulation. Main requirements of the insulation material include:

- Suitable physical and mechanical properties of the insulating material at the low temperatures
- Complete moisture and pressure sealing from the surrounding atmosphere
- A minimum of gas circulation within the insulation
- A minimum of conduction heat transfer paths through the solid constituent of the insulation
- A minimum of radiation heat transfer through the insulation

Building Insulation

Insulation in buildings (-45°C to +65°C) is used primarily to reduce heat loss during cold weather and to reduce heat **penetration** during warm weather. In the application of these insulation materials, moisture penetration should be minimized, but a complete moisture seal, is not necessary. Any moisture that is collected during warm weather when the inside of the building is cooler is driven off during cold weather when the inside of the building is warmer.

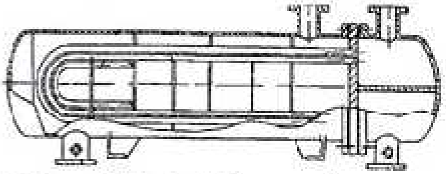
A wide range of materials is used with an **emphasis** on low cost. This favors the use of cork, rock **wool**, slag wool, glass wool, vermiculite or other granular materials, and reflective metal foils. These insulators are applied in bulk, blankets, and reinforced batts

Refractory Insulation

Refractory insulation (over +550°C) is used primarily for **lining** furnaces and high temperature retorts and crucibles for molten metals. The primary functions of the refractory insulation include:

- Providing a wear resistant hot radiating surface to assist in obtaining high furnace temperatures
- Insulating the furnace, retort, or crucible structure to prevent it from overheating
- Restricting the heat loss from the furnace, retort, or **crucible**
- Providing a lining to a retort or crucible that will resist the forces of hot molten metal in contact with or flowing over the refractory insulation

Shell and tube exchangers



The shell and tube exchanger is by far the most commonly used type of heat-transfer equipment used in the chemical and allied industries. The advantages of this type are: (1) The configuration gives a large surface area in a small volume. (2) Good mechanical layout: a good shape for pressure operation. (3) Uses well-established fabrication techniques. (4) Can be constructed from a wide range of materials. (5) Easily cleaned. (6) Well-established design procedures. The more **corrosive** fluid should be allocated to the tube-side. This will reduce the cost of expensive alloy or **clad** components. The fluid that has the greatest tendency to foul the heat-transfer surfaces should be placed in the tubes. This will give better control over the design fluid velocity, and the higher allowable velocity in the tubes will reduce fouling. Also, the tubes will be easier to clean. The higher pressure stream should be allocated to the tube-side. High-pressure tubes will be cheaper than a high-pressure shell.

Plate heat exchangers

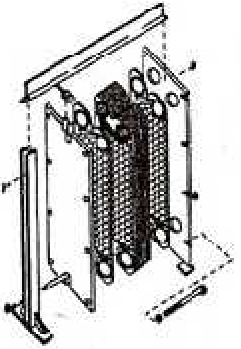


Plate heat exchangers are used extensively in the food and **beverage** industries, as they can be readily taken apart for cleaning and **inspection.** Their use in the chemical industry will depend on the relative cost for the particular application compared with a conventional shell and tube exchanger.

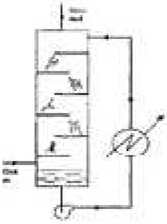
The advantages of plate heat exchangers are:

(1) Plates are attractive when material costs are high. (2) Plate heat exchangers are easier to maintain. (3) Low approach temps can be used, as low as 1 °C, compared with 5 to 10 °C for shell and tube exchangers. (4) Plate heat exchangers are more flexible, it is easy to add extra plates. (5) Plate heat exchangers are more suitable for highly viscous materials. (6) **Fouling** tends to be significantly less in plate heat exchangers.

The disadvantages of plate heat exchangers are:

(1) A plate is not a good shape to resist pressure and plate heat exchangers are not suitable for pressures greater than about 30 bar. (2) The selection of a suitable gasket is critical. (3) The maximum operating temperature is limited to about 250 °C, due to the performance of the available **gasket** materials.

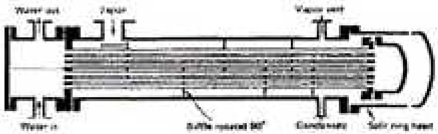
Direct-contact heat exchangers



In direct-contact heat exchangers the hot and cold streams are brought into contact without any separating wall, and high rates of heat transfer are achieved. Applications include: vacuum condensers, cooler-condensers and humidification. Water-cooling towers are a particular example of direct-contact heat exchange. In direct-contact cooler-condensers the condensed liquid is frequently used as the coolant. Direct-contact heat exchangers should be considered whenever the process stream and coolant are **compatible**.

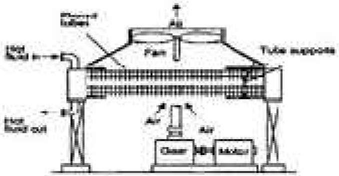
Condensers

Gravitational separation of liquid and vapor also plays an important part in the functioning of condensers, of which many designs exist, their nature determined largely by the ratio of the condensed to the uncondensed components in the fluid stream being cooled. In power station condensers, the steam is usually on the shell side, and the cooling water runs through horizontal tubes. In the process industry, tube-side condensation is common, and, in those **circumstances**, the tubes are usually vertical.



Air-cooled exchangers

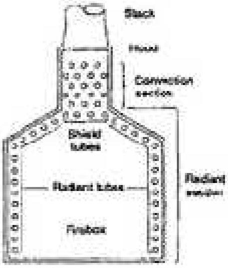
Air-cooled exchangers should be considered when cooling water is in short supply or expensive. Air-cooled exchangers consist of banks of **finned** tubes over which air is blown or drawn by fans mounted below or above the tubes. Air-cooled exchangers are packaged units, and would normally be selected and specified in consultation with the manufacturers.



Furnaces

The use of the combustion products of a fuel and air as one of the streams in a heat exchanger has been mentioned on more than one occasion. When the combustion of the fuel takes place inside the heat exchanger, rather than in an external combustion chamber (as in a gas turbine plant), the equipment may be called a furnace or fired heater.

Heat exchangers of this type take many forms, depending on the nature of the fuel (gaseous, liquid, or solid); the material to be heated (which may be oil in tubes lining the furnace wall, or a pool of molten iron, or a spark of solid clayware articles); on the magnitude of the **throughput** that must be achieved.



The Mass-Transfer Operations

Introduction

A substantial number of the unit operations of chemical engineering are concerned with the problem of changing the compositions of solutions and mixtures through methods not necessarily involving chemical reactions. When two phases of different compositions are brought into contact, a transfer of components may occur from one phase to the other, and **vice versa**. The mass-transfer operations are characterized by transfer of a substance through another on a molecular scale. For example, when water evaporates from a pool into an airstream flowing over the water surface, molecules of water vapor diffuse through those of the air at the surface into the main portion of the airstream, whence they are carried away. It is not bulk movement as a result of a pressure difference, as in pumping a liquid through a pipe, with which we are primarily concerned. In the problems at hand, the mass transfer is a result of a concentration difference, the diffusing substance moving from a place of high to one of low concentration.

Direct Contact of Two Immiscible Phases

In the mass-transfer operations, neither equilibrium phase consists of only one component. Consequently when the two phases are initially contacted, they will not (except **fortuitously**) be of equilibrium compositions. The system then attempts to reach equilibrium by a relatively slow diffusive movement of the constituents, which transfer in part between the phases in the process. Separations are therefore never complete, although, they can be brought as near completion as desired (but not totally) by appropriate **manipulations**.

Unit operation is concerned with those separation processes that depend upon differences in physical properties, rather than chemical behavior. Such processes depend either upon a difference in composition of phases at equilibrium or upon a difference in the rate of mass transfer of constituents of a mixture.

Gas-Liquid

If all components of the system distribute between the phases at equilibrium, the operation is known as fractional **distillation** (or frequently just distillation). In this instance the gas phase is created from the liquid by application of heat; or **conversely**, the liquid is created from the gas by removal of heat. For example, if a liquid solution of acetic acid and water is partially vaporized by heating, it is found that the newly created vapor phase and the **residual** liquid both contain acetic acid and water but in proportions at equilibrium which are different for the two phases and different from those in the original solution.

Both phases may be solutions, each containing, however, only one common component (or group of components) which distributes between the phases. For example, if a mixture of ammonia and air is contacted with liquid water, a large portion of the ammonia, but essentially no air, will dissolve in the liquid and in this way the air-ammonia mixture can be separated. The operation is known as gas **absorption**. On the other hand, if air is brought into contact with an ammonia-water solution, some of the ammonia leaves the liquid and enters the gas phase, an operation known as **desorption** or stripping. The difference is purely in the direction of solute transfer.

If the liquid phase is a pure liquid containing but one component while the gas contains two or more, the operation is humidification or dehumidification, depending upon the direction of transfer (this is the exception mentioned earlier). For example, contact of dry air with liquid water results in evaporation of some water into the air (**humidification** of the air). Conversely, contact of very **moist** air with pure liquid water may result in condensation of part of the moisture in the air (**dehumidification**). In both cases, diffusion of water vapor through air is involved, and we include these among the mass-transfer operations.

Gas-Solid

Classification of the operations in this category according to the number of components which appear in the two phases is again convenient.

Not all components may be present in both phases, however. If a solid which is moistened with a volatile liquid is exposed to a relatively dry gas, the liquid leaves the solid and diffuses into the gas, an operation generally known as **drying**, sometimes as desorption. A homely example is drying laundry by exposure to air, and there are many industrial counterparts such as drying lumber or the removal of moisture from a wet filter cake by exposure to dry gas. In this case, the diffusion is, of course, from the solid to the gas phase. If the diffusion takes place in the opposite direction, the operation is known as **adsorption**. For example, if a mixture of water vapor and air is brought into contact with activated silica gel, the water vapor diffuses to the solid, which retains it strongly, and the air is thus dried.

Liquid-Liquid

Separations involving the contact of two insoluble liquid phases are known as *liquid-extraction operations*. A simple example is the familiar laboratory procedure: if an acetone-water solution is shaken in a separatory funnel with carbon tetrachloride and the liquid is allowed to **settle**, a large portion of the acetone will be found in the carbon tetrachloride-rich phase and will thus have been separated from the water. A small amount of the water will also have been dissolved by the carbon tetrachloride, and a small amount of the latter will have entered the water layer, but these effects are relatively **minor**.

Solid-Liquid

Components of a solid phase can be separated by selectively dissolving the soluble part of solid with an appropriate solvent. This operation is also called **leaching** or washing. The solid must be finely divided so that the liquid solvent contacts all of it. Usually the desirable component is soluble, and the remainder of the solid is insoluble. The solute must then be recovered from the extract solution in an additional separation step.

Solid-liquid extraction is used industrially in the manufacture of instant coffee to recover the soluble coffee from the **grounds**. Other industrial applications include the extraction of oil from soy beans using hexane as a solvent and the recovery of uranium from low-grade ores by extraction with sulfuric acid or sodium carbonate solutions. Because one of the phases is a solid that does not flow like a fluid, special types of equipment are required for solid-liquid extraction.

Membrane separation

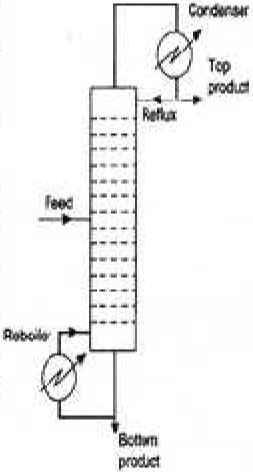
The membranes operate in different ways, depending upon the nature of the separation to be made. In general, however, they serve to prevent **intermingling** of two **miscible** phases. They also prevent ordinary hydrodynamic flow, and movement of substances through them is by diffusion. And they permit a component separation by selectively controlling passage of the components from one side to the other.

The separation of a crystalline substance from a colloid, by contact of their solution with a liquid solvent with an intervening membrane permeable only to the solvent and the dissolved crystalline substance, is known as **dialysis**.

Fractional dialysis for separating two crystalline substances in solution makes use of the difference in membrane permeability for the substances. If an electromotive force is applied across the membrane to assist in the diffusion of charged particles, the operation is **electrodialysis**. If a solution is separated from the pure solvent by a membrane which is permeable only to the solvent diffuses into the solution, an operation known as **osmosis**. by superimposing a pressure to oppose the osmotic pressure the flow of solvent is reversed, and the solvent and solute of a solution can be separated by *reverse osmosis*.

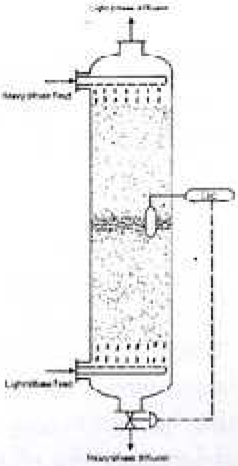
Distillation

Distillation is probably the most widely used separation process in the chemical and **allied** industries. The separation of liquid mixtures by distillation depends on differences in **volatility** between the components. Equipment types are of two kinds, tray-type or packed, stagewise or continuous. The trays function as individual stages and produce stepwise changes in concentration.



Vapor flows up the column and liquid counter-currently down the column. The vapor and liquid are brought into contact on plates, or packing. Part of the condensate from the condenser is returned to the top of the column to provide liquid flow above the feed point (reflux), and part of the liquid from the base of the column is vaporized in the reboiler and returned to provide the vapor flow. In packed towers concentration changes occur gradually. Packed towers are suited to small diameters (24in or less), whenever low pressure is desirable, whenever low **holdup** is necessary, and whenever plastic or ceramic construction is required.

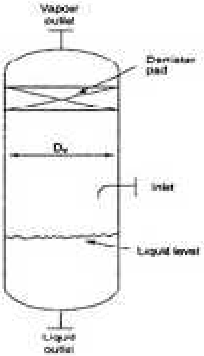
Spray Towers



Spray towers are simple gravity extractors, consisting of empty towers with **provisions** for introducing and removing liquids at the ends. The interface can be run above the top distributor, below the bottom distributor, or in the middle, depending on where the best performance is achieved. Because of severe **axial back mixing**, it is difficult to achieve the equivalent of more than one or two theoretical stages on one side of the interface. For this reason they have only rarely been applied in extraction applications.

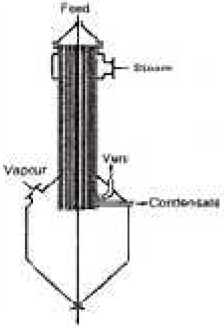
Vertical separators

The diameter of the vessel must be large enough to slow the gas down to below the velocity at which the particles will settle out. The height of the vessel outlet above the gas inlet should be sufficient to allow for **disengagement** of the liquid drops. The liquid level will depend on the hold-up time necessary for smooth operation and control, typically 10 minutes would be allowed.



Evaporator

Evaporation is the removal of a solvent by vaporization, from solids that are not volatile. It is normally used to produce a concentrated liquid, often prior to crystallization, but a dry solid product can be obtained with some specialized designs. A great variety of evaporator designs have been developed for specialized applications in particular industries. The selection of the most suitable evaporator type for a particular application will depend on the following factors: (1) The throughput required, (2) The viscosity of the feed and the increase in viscosity during evaporation, (3) The nature of the product required; solid, **slurry**, or concentrated solution, (4) The heat sensitivity of the product, (5) Whether the materials are fouling or non-fouling, (6) Whether the solution is likely to **foam**, (7) Whether direct heating can be used.



Crushing and grinding

Crushing is the first step in the process of size reduction. For some processes crushing is sufficient, but for chemical processes it is usually followed by grinding to produce a fine-sized powder. The main factors to be considered when selecting equipment for crushing and grinding are: (1) The size of the feed, (2) The size reduction ratio, (3) The required particle size distribution of the product, (4) The throughput, (5) The properties of the material: hardness, **abrasiveness**, stickiness, density, **toxicity**, **flammability**. The most commonly used equipments for coarse size reduction are jaw crashers and rotary crashers, and for grinding, ball mills or their variants: roll and tube mills.