

Units operation

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Syllabus:

- 1) Boundary layer theory .
- 2) Transfer of heat, mass and momentum .
- 3) Non-Newtonian fluids .
- 4) Mixing .

References

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Units operation

Every industrial chemical process is based on Unit Operations (physical treatment) and Unit Process (chemical treatment) to produce economically a desired product from specific raw materials. The raw materials are treated through physical steps to make it suitable for chemical reaction. So, knowledge of unit operations like 'Mixing and agitation of liquid' and 'heat flow' is very much necessary. The subject Unit Operations is based on fundamental laws & physicochemical principles. Unit Operations gives idea about science related to specific physical operation; different equipments design, material of construction and operation; and calculation of various physical parameters (mass flow, heat flow, mass balance, power and force etc.).

The Boundary Layer

11.1. INTRODUCTION

When a fluid flows over a surface, that part of the stream which is close to the surface suffers a significant retardation, and a velocity profile develops in the fluid. The velocity gradients are steepest close to the surface and become progressively smaller with distance from the surface. Although theoretically there is no outer limit at which the velocity gradient becomes zero, it is convenient to divide the flow into two parts for practical purposes.

- (1) A *boundary layer* close to the surface in which the velocity increases from zero at the surface itself to a near constant stream velocity at its outer boundary.
- (2) A region outside the boundary layer in which the velocity gradient in a direction perpendicular to the surface is negligibly small and in which the velocity is everywhere equal to the stream velocity.

The thickness of the boundary layer may be arbitrarily defined as the distance from the surface at which the velocity reaches some proportion (such as 0.9, 0.99, 0.999) of the undisturbed stream velocity.

The flow conditions in the boundary layer are of considerable interest to chemical engineers because these influence, not only the drag effect of the fluid on the surface, but also the heat or mass transfer rates where a temperature or a concentration gradient exists.

1-1) BOUNDARY LAYER THEORY APPLIED TO A THIN PLATE

It is convenient first to consider the flow over a thin plate inserted parallel to the flow of a fluid with a constant stream velocity u_s . It will be assumed that the plate is sufficiently wide for conditions to be constant across any finite width(w) of the plate which is being considered. Furthermore, the extent of the fluid in a direction perpendicular to the surface is considered as sufficiently large for the velocity of the fluid remote from the surface to be unaffected and to remain constant at the stream velocity u_s . The development of the boundary layer over flat surface is illustrated in Figure (1-1)

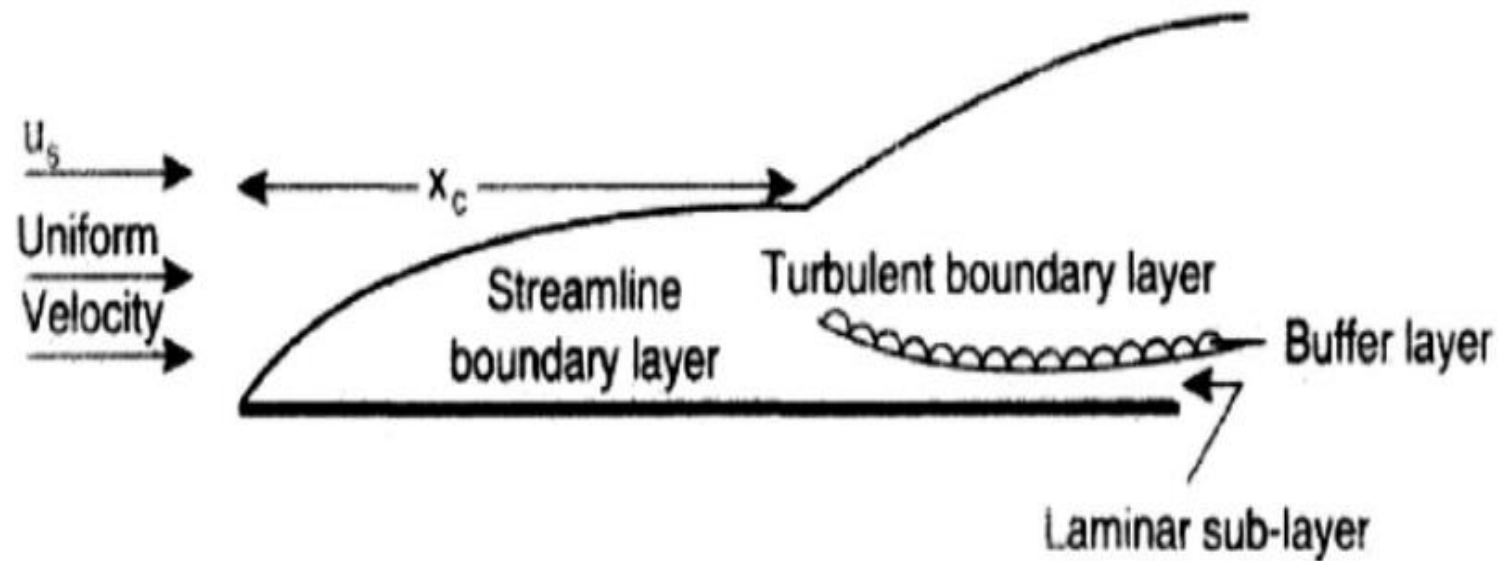


Figure (1-1) Development of the boundary layer

On the assumption that there is no slip at the surface, the fluid velocity at all points on the surface, where $y = 0$, will be zero. At some position a distance x from the leading edge, the velocity will increase from zero at the surface to approach the stream velocity u_s asymptotically.

Near the leading edge of the surface where the boundary layer thickness is small, the flow will be streamline, or laminar, and the shear stresses will arise solely from viscous shear effects. When the boundary layer thickness exceeds a critical value, the streamline flow ceases to be

stable and turbulence sets in. The important flow parameter is the Reynolds number $Re_\delta (= u_s \delta \rho / \mu)$. Because δ can be expressed as a function of x (the distance from the leading edge of the surface) the usual criterion is taken as the value of the Reynolds number $Re_x (= u_s x \rho / \mu)$. If the location of the transition point is at a distance x_c from the leading edge, then [**$Re_{x_c} = 10^5$**].

When the flow in the boundary layer is turbulent, streamline flow persists in a thin region close to the surface called the laminar sub-layer. This region is of particular importance because, in heat or mass transfer, it is where the greater part of the resistance to transfer lies. High heat and mass transfer rates therefore depend on the laminar sub-layer being thin. Separating the laminar sub-layer from the turbulent part of the boundary layer is the buffer layer, in which the contributions of the viscous effects and of the turbulent eddies are of comparable magnitudes.

1-1-A) The momentum equation

It will be assumed that a fluid of density (ρ) and viscosity (μ) flows over a plane surface and the velocity of flow outside the boundary layer is u_s . A boundary layer of thickness δ forms near the surface, and at a distance y from the surface the velocity of the fluid is reduced to a value u_x .as shown in figure(1-2)

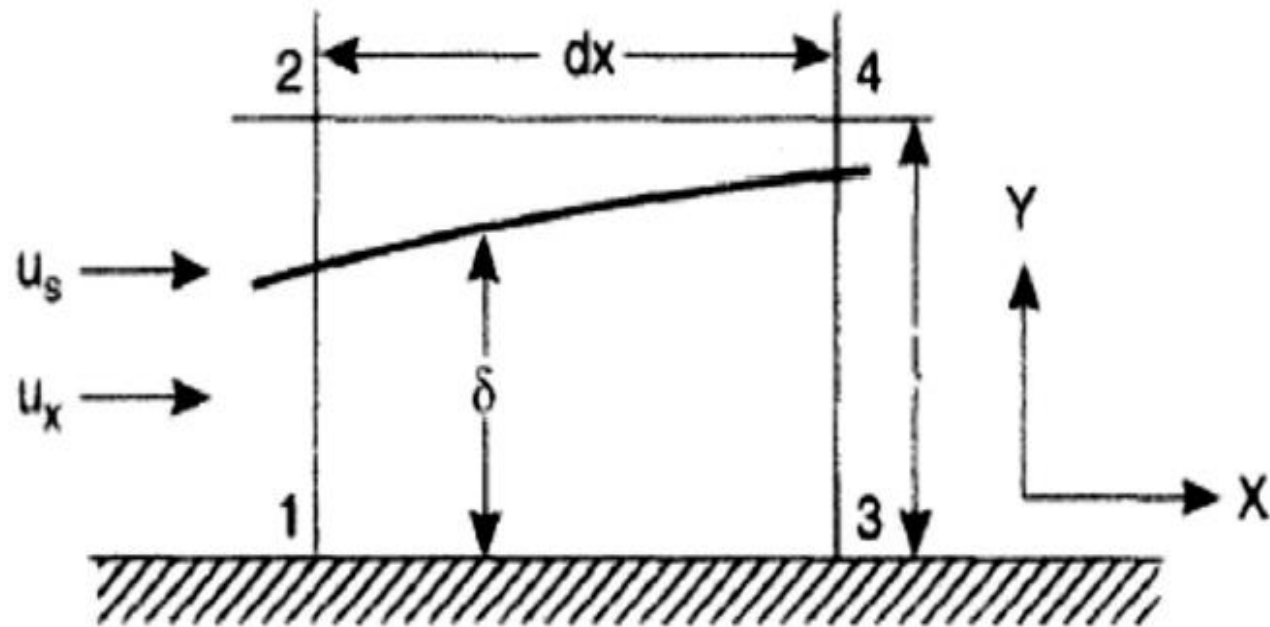


Figure (1-2) Element of boundary layer

The equilibrium is considered of an element of fluid bounded by the planes 1-2 and 3-4 at distances x and $x + dx$ respectively from the leading edge; the element is of length (l) in the direction of flow and is of depth w in the direction perpendicular to the plane 1-2-3-4. The distance (l) is greater than the boundary layer thickness δ , and conditions are constant over the width (w) . The velocities and forces in the X-direction are now considered.

At plane 1-2, mass rate of flow through a strip of thickness dy at distance y from the surface = $\rho u_x w dy$

The total flow through plane 1 -2 = $w \int_0^l \rho u_x dy$ -----(1-1)

The rate of transfer of momentum through the elementary strip
 $= \rho u_x w dy u_x = w \rho u_x^2 dy$

The total rate of transfer of momentum through plane 1 -2:

$$M_i = w \int_0^l \rho u_x^2 dy \quad \text{----- (1-2)}$$

In passing from plane 1-2 to plane 3-4, the mass flow changes by:

$$w \frac{\partial}{\partial x} \left(\int_0^l \rho u_x dy \right) dx \quad \text{----- (1-3)}$$

and the momentum flux changes by:

$$M_{ii} - M_i = w \frac{\partial}{\partial x} \left(\int_0^l \rho u_x^2 dy \right) dx \quad \text{----- (1-4)}$$

where M_{ii} is the momentum flux across the plane 3-4.

A mass flow of fluid equal to the difference between the flows at planes 3-4 and 1-2 must therefore occur through plane 2-4.

Momentum, Heat, and Mass Transfer

In most of the unit operations encountered in the chemical and process industries, one or more of the processes of momentum, heat, and mass transfer is involved. Thus, in the flow of a fluid under adiabatic conditions through a bed of granular particles, a pressure gradient is set up in the direction of flow and a velocity gradient develops approximately perpendicularly to the direction of motion in each fluid stream; momentum transfer then takes place between the fluid elements which are moving at different velocities. If there is a temperature difference between the fluid and the pipe wall or the particles, heat transfer will take place as well, and the convective component of the heat transfer will be directly affected by the flow pattern of the fluid. Here, then, is an example of a process of simultaneous momentum and heat transfer in which the same fundamental mechanism is affecting both processes. Fractional distillation and gas absorption are frequently carried

out in a packed column in which the gas or vapour stream rises countercurrently to a liquid. The function of the packing in this case is to provide a large interfacial area between the phases and to promote turbulence within the fluids. In a very turbulent fluid, the rates of transfer per unit area of both momentum and mass are high; and as the pressure drop rises the rates of transfer of both momentum and mass increase together. In some cases, momentum, heat, and mass transfer all occur simultaneously as, for example, in a water-cooling tower (see Chapter 13), where transfer of sensible heat and evaporation both take place from the surface of the water droplets. It will now be shown not only that the process of momentum, heat, and mass transfer are physically related, but also that quantitative relations between them can be developed.

Another form of interaction between the transfer processes is responsible for the phenomenon of *thermal diffusion* in which a component in a mixture moves under the action of a temperature gradient. Although there are important applications of thermal diffusion, the magnitude of the effect is usually small relative to that arising from concentration gradients.

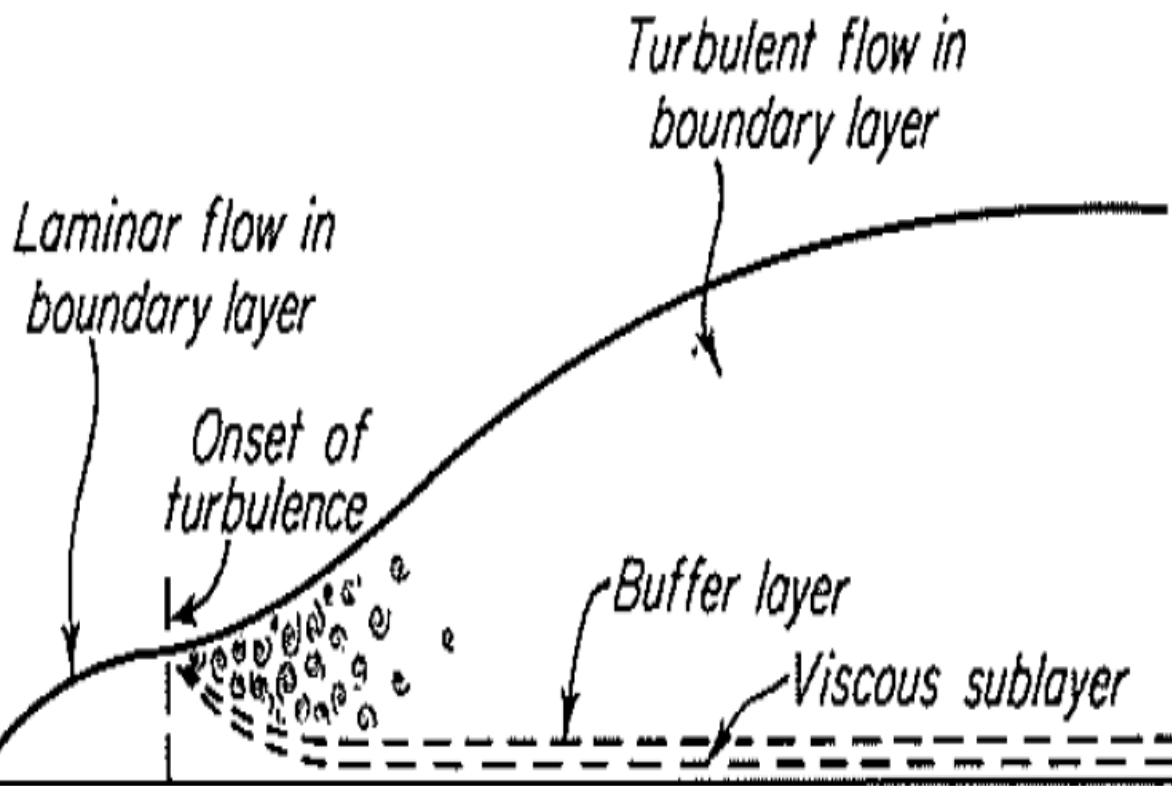
When a fluid is flowing under streamline conditions over a surface, a forward component of velocity is superimposed on the random distribution of velocities of the molecules, and movement at right angles to the surface occurs solely as a result of the random motion

When a fluid flows under **turbulent conditions over a surface**, the flow can conveniently be divided into three regions:

1. At the surface, **the laminar sub-layer**, in which the only motion at right angles to the surface is due to molecular diffusion. The resistance to transfer of momentum, heat and mass concentrated in this region and can be reduced by increasing the Reynolds number.
2. Next, **the buffer layer**, in which molecular diffusion and eddy motion are of comparable magnitude (50% sub-layer + 50% turbulent core) .
3. Finally, over the greater part of the fluid, **the turbulent region** in which eddy motion is large compared with molecular diffusion.

In addition to momentum, both heat and mass can be transferred either by molecular diffusion alone or by molecular diffusion combined with eddy diffusion. Because the effects of eddy diffusion are generally far greater than those of the molecular diffusion, *the main resistance to transfer will lie in the region where only molecular diffusion is occurring.*

BOUNDARY-LAYER THICKNESS



Turbulent flow in boundary layer

Laminar flow in boundary layer

Onset of turbulence

Buffer layer

Viscous sublayer

DISTANCE FROM LEADING EDGE, x

12.2. TRANSFER BY MOLECULAR DIFFUSION

12.2.1. Momentum transfer

When the flow characteristics of the fluid are *Newtonian*, the shear stress R_y in a fluid is proportional to the velocity gradient and to the viscosity.

Thus, for constant density: $R_y = -\mu \frac{du_x}{dy} = -\frac{\mu}{\rho} \frac{d(\rho u_x)}{dy}$ (Equation 12.1) **Newton's law**

where u_x is the velocity of the fluid parallel to the surface at a distance y from it.

The shear stress R_y within the fluid, at a distance y from the boundary surface, is a measure of the rate of transfer of momentum per unit area at right angles to the surface.

Since (ρu_x) is the momentum per unit volume of the fluid, the rate of transfer of momentum per unit area is proportional to the gradient in the Y -direction of the momentum per unit volume. The negative sign indicates that momentum is transferred from the fast- to the slow-moving fluid and the shear stress acts in such a direction as to oppose the motion of the fluid.

12.2.2. Heat transfer

From the definition of thermal conductivity, the heat transferred per unit time through unit area at a distance y from the surface is given by:

$$q_y = -k \frac{d\theta}{dy} = -\left(\frac{k}{C_p \rho}\right) \frac{d(C_p \rho \theta)}{dy} \quad \text{Fourier's law} \quad (12.2)$$

where C_p is the specific heat of the fluid at constant pressure, θ the temperature, and k the thermal conductivity. C_p and ρ are both assumed to be constant.

The term $(C_p \rho \theta)$ represents the heat content per unit volume of fluid and therefore the flow of heat is proportional to the gradient in the Y -direction of the heat content per unit volume. The proportionality constant $k/C_p \rho$ is called the thermal diffusivity D_H .

12.2.3. Mass transfer

It is shown in Chapter 10, from Fick's Law of diffusion, that the rate of diffusion of a constituent **A** in a mixture is proportional to its concentration gradient.

Thus, from equation 10.4:

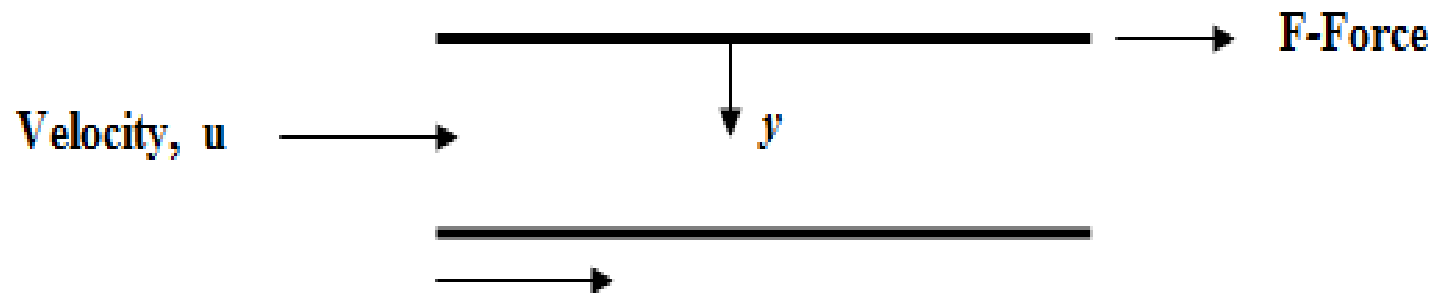
$$N_A = -D \frac{dC_A}{dy} \quad \dots \dots \dots \text{Fick's law ...12.3)}$$

where N_A is the molar rate of diffusion of constituent **A** per unit area, C_A the molar concentration of constituent **A** and D the diffusivity.

The essential similarity between the three processes is that the rates of transfer of momentum, heat, and mass are all proportional to the concentration gradients of these quantities. In the case of gases the proportionality constants μ/ρ , D_H , and D , all of which have the dimensions length²/time, all have a physical significance. For liquids the

Viscosity:

If a fluid is flowing past a wall, the velocity of the fluid is zero at the wall. Suppose the fluid flows with no cross mixing (low velocity or laminar flow) through the opening between two planes:



Viscosity: is the property of a fluid which gives rise to forces that resist the relative movement of adjacent layers in the fluid. These viscous forces arise from forces existing between the molecules in the fluid. These forces are called 'shear forces'.

$$\text{Shear rate} = \frac{du}{dy}$$

$$\text{Shear stress } (R_y) = \frac{F}{A} \quad \dots \dots \dots \quad \text{on plane parallel to wall}$$

$$\text{Shear stress must be proportional to shear rate: } R_y = \frac{F}{A} \propto \frac{du}{dy}$$

$$\text{The viscosity is the proportionality constant } \rightarrow R_y = -\mu \frac{du}{dy}$$

Where:

$$\mu : \text{ is the dynamic viscosity of the fluid} = \left(\frac{dy}{du} \right) \left(\frac{F}{A} \right) = \left(\frac{m}{m/s} \right) \left(\frac{N}{m^2} \right) = \frac{N \cdot s}{m^2} = \frac{kg}{m \cdot s} = \text{Pa} \cdot s$$

$$1 \text{ poise} = 1 \frac{gm}{cm \cdot s} = 0.1 \frac{kg}{m \cdot s}$$

$$1 \text{ centipoise} = 0.01 \text{ poise}$$

$$\nu = \frac{\mu}{\rho} : \text{ is the kinematic viscosity of the fluid} = \left(\frac{\frac{kg}{m \cdot s}}{\frac{kg}{m^3}} \right) = \frac{m^2}{s}$$

$$1 \text{ stock} = 1 \frac{cm^2}{s} \quad \text{and} \quad 1 \text{ centistock} = 0.01 \text{ stock}$$

Reynolds number (Re):

Reynolds number is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. *The Reynolds number is also defined as the ratio of momentum forces to viscous forces* and consequently quantifies the relative importance of these two types of forces for given flow conditions.

$$\text{Re} = \frac{\text{momentum force}}{\text{viscous force}} = \frac{u d}{\nu} = \frac{\rho u d}{\mu}$$

Where:

u : is the fluid velocity, $\left(\frac{\text{m}}{\text{s}}\right)$.

d : is the pipe diameter, (m).

ν : is the **kinematic viscosity** of the fluid, $\left(\frac{\mu}{\rho}\right)$, $\left(\frac{\text{m}^2}{\text{s}}\right)$.

μ : is the dynamic diameter viscosity of the fluid, (Pa.s) or $\left(\frac{\text{N.s}}{\text{m}^2}\right)$.

For flow in a pipe:

1. $Re < 2100$ the flow is laminar
2. $2100 < Re < 4000$ the flow is transitional
3. $Re > 4000$ the flow is turbulent

For flow over a flat plate:

1. $Re < 5 \times 10^5$ the flow is laminar
2. $3 \times 10^5 < Re < 5 \times 10^5$ the flow is transitional
3. $Re > 5 \times 10^5$ the flow is turbulent

Prandtl number (Pr):

Prandtl number is a dimensionless number defined as the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity. That is, the Prandtl number is given as:

$$Pr = \frac{\text{Viscous diffusion rate}}{\text{Thermal diffusion rate}} = \frac{\nu}{\alpha} = \frac{\mu/\rho}{k/c_p \rho} = \frac{\mu c_p}{k}$$

Diffusivity:

Diffusivity is a proportionality constant between the molar flux due to molecular diffusion and the gradient in the concentration of the species (or the driving force for diffusion). Diffusion coefficient is generally prescribed for a given pair of species. For a multi-component system, it is prescribed for each pair of species in the system. The higher the diffusivity (of one substance with respect to another), the faster they diffuse into each other.

$$N_A = -D \frac{dC_A}{dy}$$

Where:

D : is the diffusivity $\left(\frac{\text{m}^2}{\text{s}} \right)$.

Schmidt number (Sc):

Schmidt number is a dimensionless number defined as the ratio of momentum diffusivity (kinematic viscosity) to the diffusivity of mass transfer. That is, the Schmidt number is given as:

$$\text{Sc} = \frac{\text{Viscous diffusion rate}}{\text{Mass diffusion rate}} = \frac{\nu}{D} = \frac{\mu/\rho}{D} = \frac{\mu}{\rho D}$$

12.3.1. The nature of turbulent flow

In turbulent flow there is a complex interconnected series of circulating or eddy currents in the fluid, generally increasing in scale and intensity with increase of distance from any boundary surface. If, for steady-state turbulent flow, the velocity is measured at any fixed point in the fluid, both its magnitude and direction will be found to vary in a random manner with time. This is because a random velocity component, attributable to the circulation of the fluid in the eddies, is superimposed on the steady state mean velocity. No net motion arises from the eddies and therefore their time average in any direction must be zero. The instantaneous magnitude and direction of velocity at any point is therefore the vector sum of the steady and fluctuating components.

If the magnitude of the fluctuating velocity component is the same in each of the three principal directions, the flow is termed *isotropic*. If they are different the flow is said to be *anisotropic*. Thus, if the root mean square values of the random velocity components in the X , Y and Z directions are respectively $\sqrt{u_{Ex}^2}$, $\sqrt{u_{Ey}^2}$ and $\sqrt{u_{Ez}^2}$, then for isotropic turbulence:

$$\sqrt{u_{Ex}^2} = \sqrt{u_{Ey}^2} = \sqrt{u_{Ez}^2} \quad (12.15)$$

There are two principal characteristics of turbulence. One is the *scale* which is a measure of the mean size of the eddies, and the other is the *intensity* which is a function of the circulation velocity ($\sqrt{u_E^2}$) within the eddies. Both the scale and the intensity increase as the distance from a solid boundary becomes greater. During turbulent flow in a pipe, momentum is transferred from large eddies in the central core through successively smaller eddies as the walls are approached. Eventually, when the laminar sub-layer is reached the eddies die out completely. However, the laminar sub-layer should not be regarded as a completely discrete region, because there is evidence that from time to time eddies do penetrate and occasionally completely disrupt it.

The intensity of turbulence I is defined as the ratio of the mean value of the fluctuating component of velocity to the steady state velocity. For flow in the X -direction parallel to a surface this may be written as:

$$I = \frac{\sqrt{\frac{1}{3}(\overline{u_{Ex}^2} + \overline{u_{Ey}^2} + \overline{u_{Ez}^2})}}{u_x} \quad (12.16)$$

For isotropic turbulence, from equation 12.15, this becomes:

$$I = \frac{\sqrt{\overline{u_E^2}}}{u_x} \quad (12.17)$$

The intensity of turbulence will vary with the geometry of the flow system. Typically, for a fluid flowing over a plane surface or through a pipe, it may have a value of between

12.3.2. Mixing length and eddy kinematic viscosity

PRANDTL^(2,3) and TAYLOR⁽⁴⁾ both developed the concept of a *mixing length* as a measure of the distance which an element of fluid must travel before it loses its original identity and becomes fully assimilated by the fluid in its new position. Its magnitude will be of the same order as the scale of turbulence or the eddy size. The mixing length is analogous in concept to the *mean free path* of gas molecules which, according to the kinetic theory is the mean distance a molecule travels before it collides with another molecule and loses its original identity.

In turbulent flow over a surface, a velocity gradient, and hence a momentum gradient, exists within the fluid. Any random movement perpendicular to the surface gives rise to a momentum transfer. Elements of fluid with high velocities are brought from remote regions towards the surface and change places with slower moving fluid elements. This mechanism is essentially similar to that involved in the random movement of molecules in a gas. It is therefore suggested that an *eddy kinematic viscosity* E for eddy transport may be defined which is analogous to the kinematic viscosity μ/ρ for molecular transport. Then for isotropic turbulence:

$$E \propto \lambda_E \mu_E \quad (12.18)$$

where λ_E is the mixing length, and

μ_E is some measure of the linear velocity of the fluid in the eddies.

It is assumed throughout that no mixing takes place with the intervening fluid when an eddy transports fluid elements over a distance equal to the mixing length.

Close to a surface $R_y \rightarrow R_0$, the value at the surface.

The shear stress R acting on the surface must be equal and opposite to that in the fluid in contact with the surface, that is $R = -R_0$, and:

$$\therefore \sqrt{\frac{R}{\rho}} = \lambda_E \frac{du_x}{dy} \quad (12.26)$$

$\sqrt{R/\rho}$ is known as the *shearing stress velocity* or *friction velocity* and is usually denoted by u^* .

In steady state flow over a plane surface, or close to the wall for flow in a pipe, u^* is constant and equation 12.26 can be integrated provided that the relation between λ_E and y is known. λ_E will increase with y and, if a linear relation is assumed, then:

$$\lambda_E = K y \quad (12.27)$$

12.4. UNIVERSAL VELOCITY PROFILE

For fully developed turbulent flow in a pipe, the whole of the flow may be regarded as lying within the boundary layer. The cross-section can then conveniently be divided into three regions:

- (a) The *turbulent core* in which the contribution of eddy transport is so much greater than that of molecular transport that the latter can be neglected.
- (b) The *buffer layer* in which the two mechanisms are of comparable magnitude.
- (c) The *laminar sub-layer* in which turbulent eddies have effectively died out so that only molecular transport need be considered.

It is now possible to consider each of these regions in turn and to develop a series of equations to represent the velocity over the whole cross section of a pipe. Together, they constitute the *Universal Velocity Profile*.

12.4.4. Velocity profile for all regions

For a smooth pipe, therefore, the complete Universal Velocity Profile is given by:

$$0 < y^+ < 5 \quad u^+ = y^+ \quad \text{(equation 12.40)}$$

$$5 < y^+ < 30 \quad u^+ = 5.0 \ln y^+ - 3.05 \quad \text{(equation 12.42)}$$

$$y^+ > 30 \quad u^+ = 2.5 \ln y^+ + 5.5 \quad \text{(equation 12.37)}$$

1.6 Newton's Law of Viscosity and Momentum Transfer

Consider two parallel plates of area (A), distance (dz) apart shown in Figure (1). The space between the plates is filled with a fluid. The lower plate travels with a velocity (u) and the upper plate with a velocity ($u-du$). The small difference in velocity (du) between the plates results in a resisting force (F) acting over the plate area (A) due to viscous frictional effects in the fluid.

Thus the force (F) must apply to the lower plate to maintain the difference in velocity (du) between the two plates. The force per unit area (F/A) is known as the shear stress (τ).

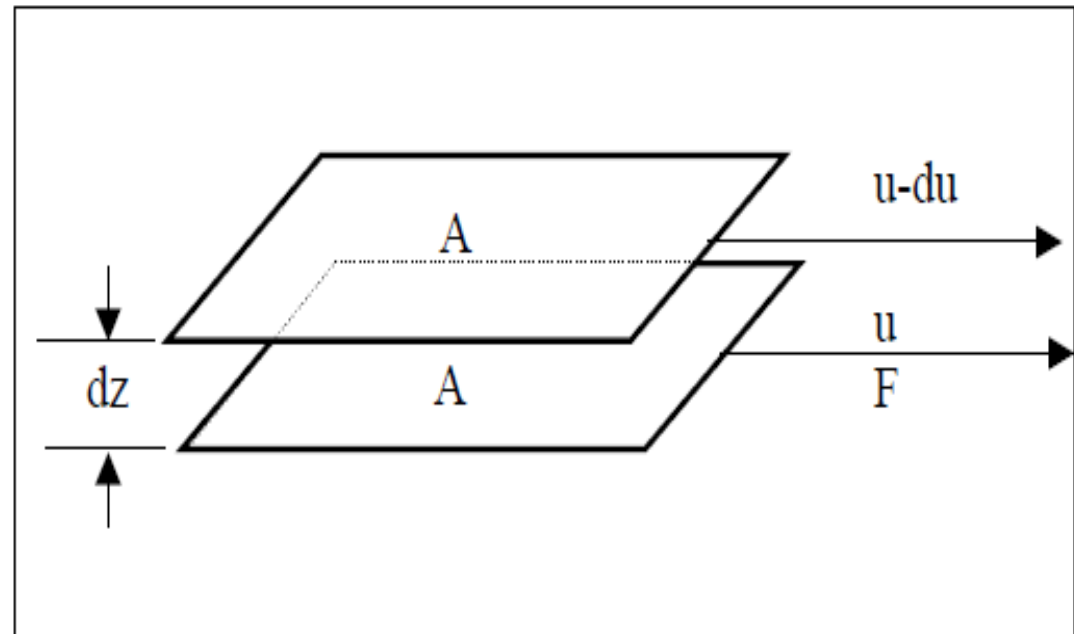


Figure (1) Shear between two plates

Newton's law of viscosity states that:

$$\tau \propto -\frac{du}{dz} \Rightarrow \tau = -\mu \frac{du}{dz}$$

Fluids, which obey this equation, are called "Newtonian Fluids" and Fluids, don't obey this equation, are called "non-Newtonian Fluids".

Note: Newton's law of viscosity holds for Newtonian fluids in laminar flow.

Momentum (shear stress) transfers through the fluid from the region of high velocities to region of low velocities, and the rate of momentum transfer increase with increasing the viscosity of fluids.

1.7 Newtonian and non-Newtonian fluids

The plot of shear stress (τ) against shear rate ($\dot{\gamma} \equiv \frac{du}{dz}$) is different in Newtonian fluids than that in non-Newtonian fluids as shown in Figure (2).

For Newtonian fluids the plot give a straight line from the origin but for non-Newtonian fluids the plot gives different relations than that of Newtonian some of these relations are given in Figure (2).

- A- Newtonian fluids
- B- non-Newtonian (pseudoplastic)
- C- non-Newtonian (dilatant)
- D- non-Newtonian (Bingham)

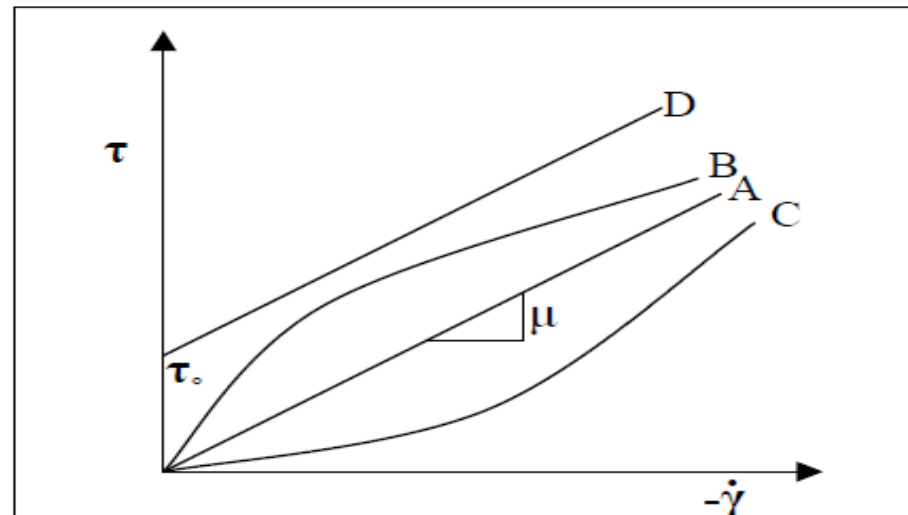


Figure (2): Shear stress (τ) against shear rate ($-\dot{\gamma} \equiv -\frac{du}{dz}$)

AGITATION OF LIQUIDS

PURPOSES OF AGITATION. Liquids are agitated for a number of purposes, depending on the objectives of the processing step. These purposes include

1. Suspending solid particles
2. Blending miscible liquids, e.g., methyl alcohol and water
3. Dispersing a gas through the liquid in the form of small bubbles
4. Dispersing a second liquid, immiscible with the first, to form an emulsion or suspension of fine drops
5. Promoting heat transfer between the liquid and a coil or jacket

Often one agitator serves several purposes at the same time, as in the catalytic hydrogenation of a liquid. In a hydrogenation vessel the hydrogen gas is dispersed through the liquid in which solid particles of catalyst are suspended, with the heat of reaction simultaneously removed by a cooling coil and jacket.

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AGITATION EQUIPMENT. Liquids are most often agitated in some kind of tank or vessel, usually cylindrical in form and with a vertical axis. The top of the vessel may be open to the air; more usually it is closed. The proportions of the tank vary widely, depending on the nature of the agitation problem. A standardized design such as that shown in Fig. 9.1, however, is applicable in many situations. The tank bottom is rounded, not flat, to eliminate sharp corners or regions into

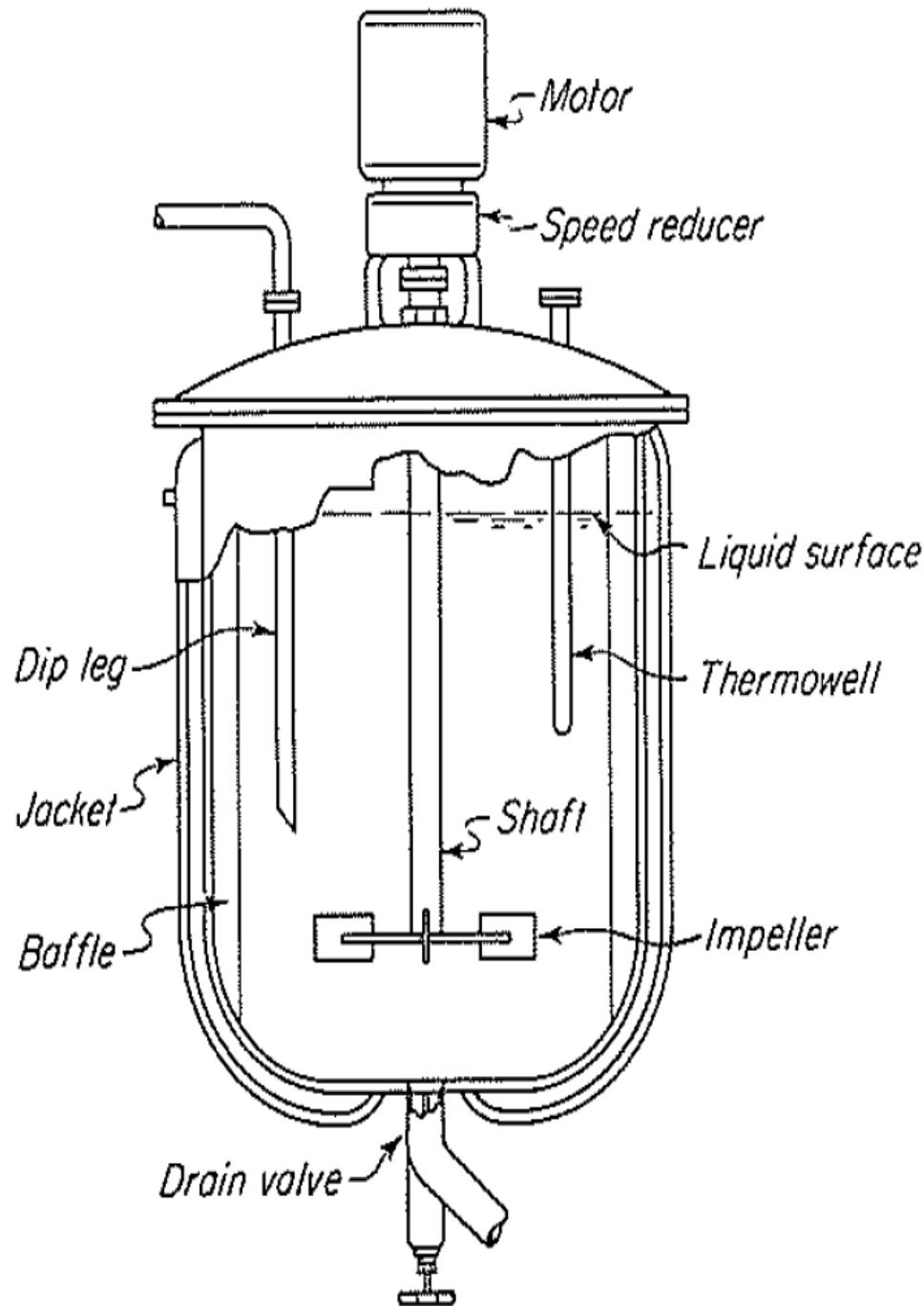


FIGURE 9.1
Typical agitation process vessel.

which fluid currents would not penetrate. The liquid depth is approximately equal to the diameter of the tank. An impeller is mounted on an overhung shaft, i.e., a shaft supported from above. The shaft is driven by a motor, sometimes directly connected to the shaft but more often connected to it through a speed-reducing gearbox. Accessories such as inlet and outlet lines, coils, jackets, and wells for thermometers or other temperature-measuring devices are usually included.

The impeller creates a flow pattern in system, causing the liquid to circulate through the vessel and return eventually to the impeller. Flow patterns in agitated vessels are discussed in detail later in this chapter.

IMPELLERS. Impeller agitators are divided into two classes: those that generate currents parallel with the axis of the impeller shaft and those that generate currents in a tangential or radial direction. The first are called *axial-flow impellers*, the second *radial-flow impellers*.

The three main types of impellers are propellers, paddles, and turbines. Each type includes many variations and subtypes, which will not be considered here. Other special impellers are also useful in certain situations, but the three main types solve perhaps 95 percent of all liquid-agitation problems.

Propellers. A propeller is an axial-flow, high-speed impeller for liquids of low viscosity. Small propellers turn at full motor speed, either 1150 or 1750 r/min; larger ones turn at 400 to 800 r/min. The flow currents leaving the impeller continue through the liquid in a given direction until deflected by the floor or wall of the vessel. The highly turbulent swirling column of liquid leaving the impeller entrains stagnant liquid as it moves along, probably considerably more than an equivalent column from a stationary nozzle would. The propeller blades vigorously cut or shear the liquid. Because of the persistence of the flow currents, propeller agitators are effective in very large vessels.

A revolving propeller traces out a helix in the fluid, and if there were no slip between liquid and propeller, one full revolution would move the liquid longitudinally a fixed distance depending on the angle of inclination of the propeller blades. The ratio of this distance to the propeller diameter is known as the *pitch* of the propeller. A propeller with a pitch of 1.0 is said to have *square pitch*.

A typical propeller is illustrated in Fig. 9.2a. Standard three-bladed marine propellers with square pitch are most common; four-bladed, toothed, and other designs are employed for special purposes.

Propellers rarely exceed 18 in. in diameter regardless of the size of the vessel. In a deep tank two or more propellers may be mounted on the same shaft, usually directing the liquid in the same direction. Sometimes two propellers work in opposite directions, or in "push-pull," to create a zone of especially high turbulence between them.

Paddles. For the simpler problems an effective agitator consists of a flat paddle turning on a vertical shaft. Two-bladed and four-bladed paddles are common. Sometimes the blades are pitched; more often they are vertical. Paddles turn at

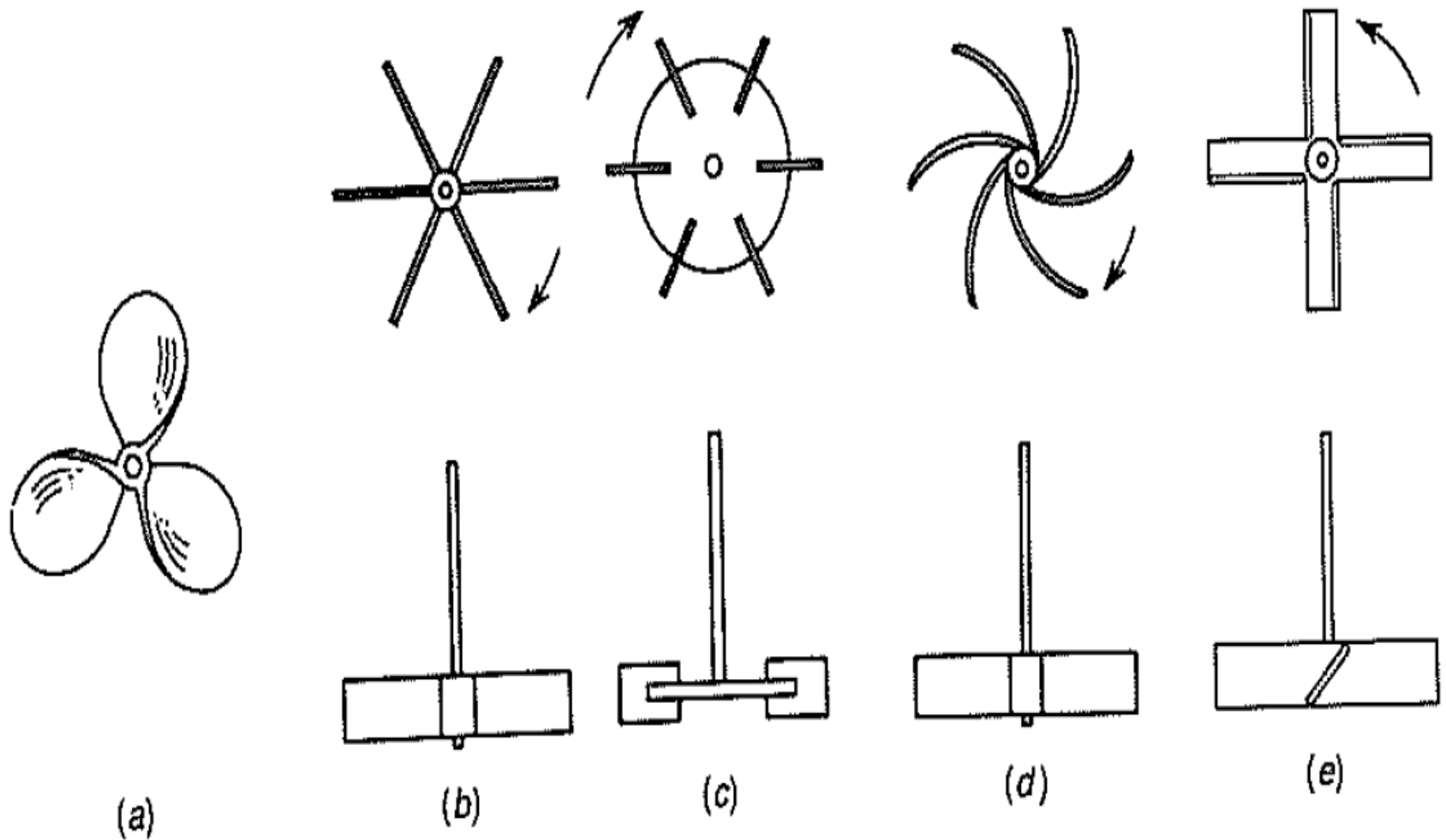


FIGURE 9.2

Mixing impellers: (a) three-blade marine propeller; (b) open straight-blade turbine; (c) bladed disk turbine; (d) vertical curved-blade turbine; (e) pitched-blade turbine.

slow to moderate speeds in the center of a vessel; they push the liquid radially and tangentially with almost no vertical motion at the impeller unless the blades are pitched. The currents they generate travel outward to the vessel wall and then either upward or downward. In deep tanks several paddles are mounted one above the other on the same shaft. In some designs the blades conform to the shape of a dished or hemispherical vessel so that they scrape the surface or pass over it with close clearance. A paddle of this kind is known as an *anchor agitator*. Anchors are useful for preventing deposits on a heat-transfer surface, as in a jacketed process vessel, but they are poor mixers. They nearly always operate in conjunction with a higher speed paddle or other agitator, usually turning in the opposite direction.

Industrial paddle agitators turn at speeds between 20 and 150 r/min. The total length of a paddle impeller is typically 50 to 80 percent of the inside diameter of the vessel. The width of the blade is one-sixth to one-tenth its length. At very slow speeds a paddle gives mild agitation in an unbaffled vessel; at higher speeds baffles become necessary. Otherwise the liquid is swirled around the vessel at high speed but with little mixing.

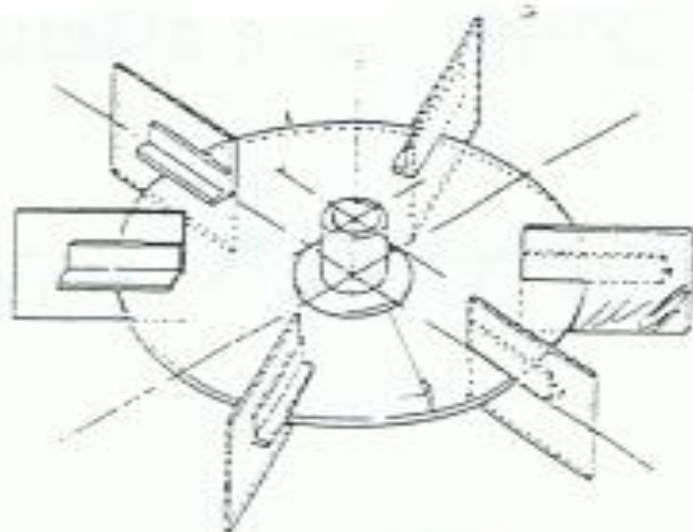
Turbines. Some of the many designs of turbine are shown in Fig. 9.2*b, c, d,* and *e*. Most of them resemble multibladed paddle agitators with short blades, turning at high speeds on a shaft mounted centrally in the vessel. The blades may be straight or curved, pitched or vertical. The diameter of the impeller is smaller than with paddles, ranging from 30 to 50 percent of the diameter of the vessel.

Turbines are effective over a very wide range of viscosities. In low-viscosity liquids turbines generate strong currents that persist throughout the vessel, seeking out and destroying stagnant pockets. Near the impeller is a zone of rapid currents, high turbulence, and intense shear. The principal currents are radial and tangential. The tangential components induce vortexing and swirling, which must be stopped by baffles or by a diffuser ring if the impeller is to be most effective.

9.2 Types of Agitators

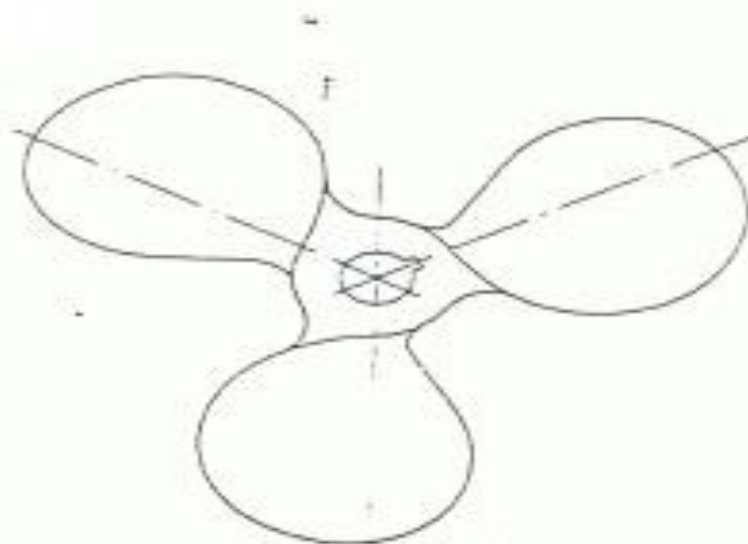
In general, agitators can be classified into the following two types: -

- 1- Agitators with a small blade area, which rotate at high speeds. These include turbines and marine type propellers.
- 2- Agitators with a large blade area, which rotate at low speeds. These include anchors, and Paddles, and helical screws.



Six-blade flat blade turbine

مستوی



مروحة بحرية
Marine Propeller

⊗ The second group is more effective than the first in the mixing of high viscosity-liquids.

For a liquid mixed in a tank with a rotating agitator, the shear rate is greatest in the intermediate vicinity of agitator. In fact the shear rate decreases exponentially with distance from the agitator. Thus the shear stresses and strains vary greatly throughout an

of shear rate at a given temperature, its viscosity will be the same at all points in the tank. In contrast the apparent viscosity of a non-Newtonian liquid varies throughout the tank. This in turn significantly influences the mixing process.

The mean shear $\dot{\gamma}_m$ produced by an agitator in a mixing tank is proportional to the rotational speed of the agitator N

$$\text{i.e. } \dot{\gamma}_m \propto N \quad \Rightarrow \dot{\gamma}_m = KN$$

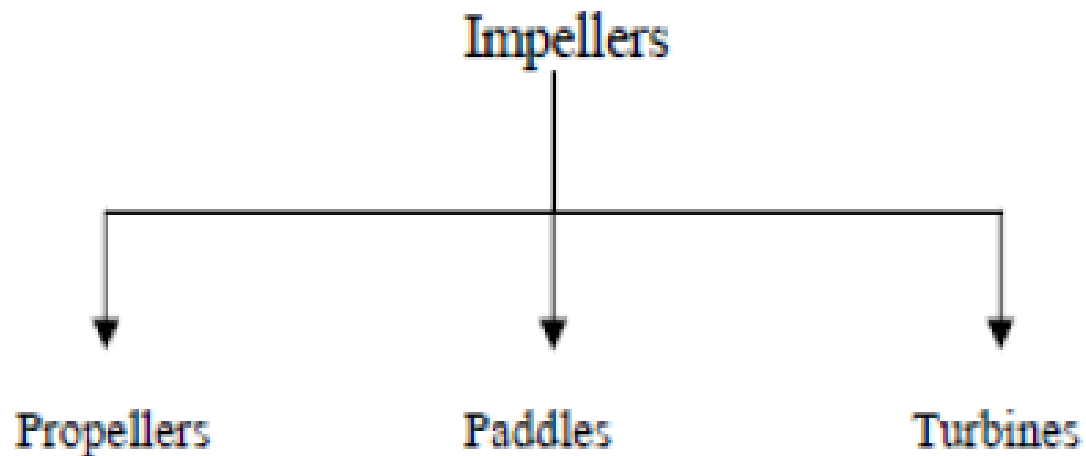
where, K is a dimensionless proportionality constant for a particular system.

It is desirable to produce a particular mixing result in the minimum time (t) and with the minimum input power per unit volume (P_A/V). Thus the efficiency function (E) can be defined as

$$E = \left(\frac{1}{P_A/V} \right) \left(\frac{1}{t} \right)$$

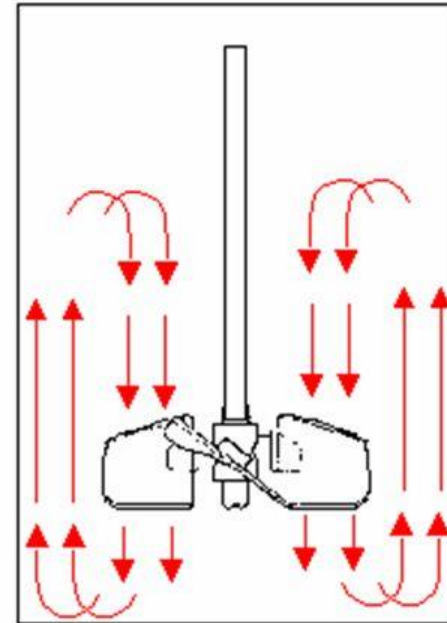
Impellers can be further classified principally into three sub-types

- **Propellers**
- **Paddles**
- **Turbines**



(i) Propellers:

- Create an axial-flow.
- Flow of currents is pushed in downward direction.
- High speed for low viscosity liquid.
- Effective in very large tanks.
- suitable for mixing of low viscose liquids, particle suspension.
- In a deep tank, 2 or more propellers may be mounted on the same shaft.



With axial impellers, the liquid is pushed in a downward direction; that is, along the axis of the reactor.

Paddles

Paddles turn at slow to moderate speeds in the center of a vessel; they push the liquid radial and tangentially with almost no vertical motion at impeller unless the blades are pitched. In deep tanks several paddles are mounted one above the other on the

Same shaft



Turbines

There are 4 types of turbine impeller

- The straight-blade turbine
- Disc turbine
- Concave blade CD-6 disc turbine
- Pitched-blade turbine



Turbines are effective over a very wide range of viscosities. In low-viscosity liquids turbines generate strong currents which persist throughout the vessel, seeking out and destroying stagnant pockets. Near the impeller is a zone of rapid currents, high turbulence, and intense shear.

In general, agitators can be classified into the following two groups.

1. Agitators with a small blade area which rotate at high speeds. These include turbines and marine type propellers.
2. Agitators with a large blade area which rotate at low speeds. include anchors, paddles and helical screws.

