SHROFF S. R. ROTARY INSTITUTE OF CHEMICAL TECHNOLOGY
ANKLESHWAR

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Flow past immersed bodies

Flow Past immersed body

Drag : The force in the direction of flow exerted by the fluid on the solid is called drag. By newton’s third law of motion, an equal and opposite net force is exerted by the body on the fluid.

When the wall of the body is parallel with direction the direction of flow as in case of the thin flat plate. The only drag force is the wall shear

More generally , however , the wall of an immerged body makes an angle with the direction of flow. Then the component of the wall shear in the direction of flow contributes to drag.

An extreme example is the drag of the flat plate perpendicular to the flow ,shown in the fig .3.9 ,

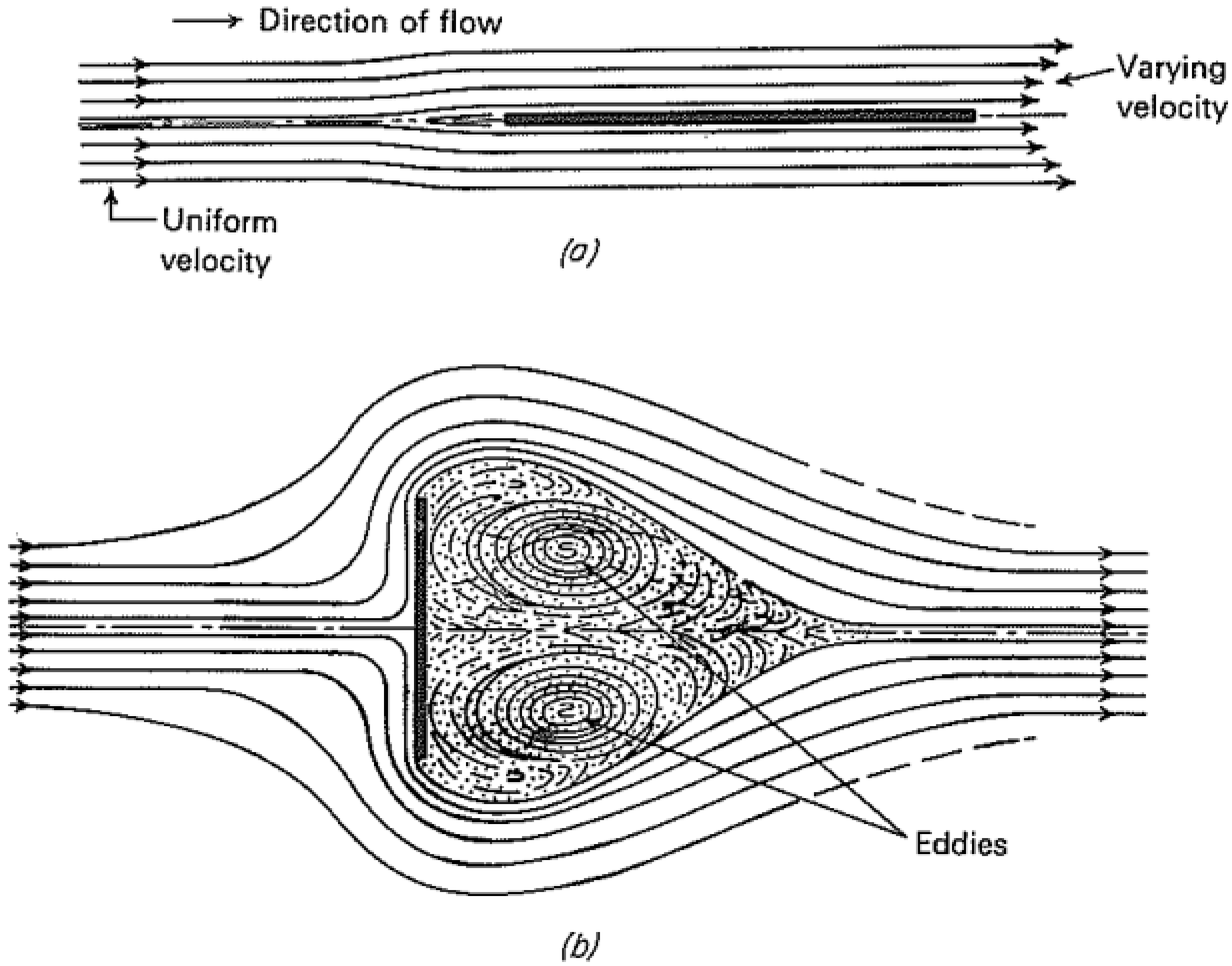


FIGURE 3.9
Flow past flat plate: (*a*) flow parallel with plate; (*b*) flow perpendicular to plate.

Flow Past immersed body

- Also, the fluid pressure which act in a direction normal to the wall, possesses a component in the direction of flow and this component also contributes the drag.
- The total drag on an element of area is the sum of the two componets.
- Figure 7.1 shows the pressure and shear forces acting on an element of area dA inclined at an angle of 90°-α to the direction of flow.
- The drag from wall shear is **τ_w sinα dA** and that from pressure is **p cosα dA**

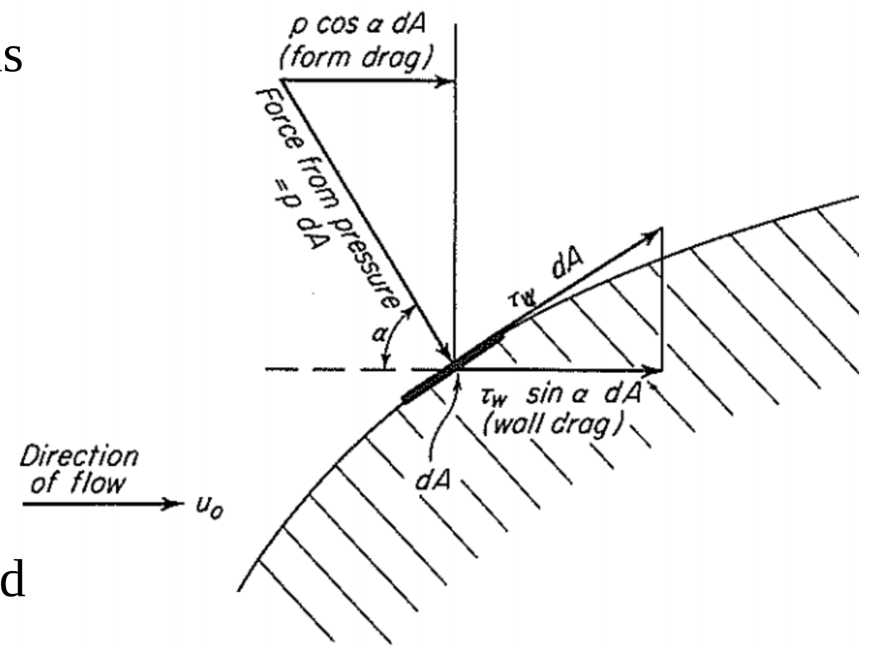


FIGURE 7.1
Wall drag and form drag on immersed body.

The total drag on the body is the sum of the integrals of these quantities , each evaluated over the entire surface of the body in contact with the fluid.

The total integrated drag from wall shear is called *wall drag*, and the total integrated drag from pressure is called *form drag*.

In potential flow, $\tau_w = 0$, and there is no wall drag. Also, the pressure drag in the direction of flow is balanced by an equal force in the opposite direction, and the integral of the form drag is zero. There is no net drag in potential flow.

Drag coefficient

If F_D is the total drag, the average drag per unit projected area is F_D/A_p. Just as the friction factor f is defined as the ratio of τ_w to the product of the density of the fluid and the velocity head, so the drag coefficient C_D is defined as the ratio of F_D/A_p to this same product, or

$$C_D \equiv \frac{F_D/A_p}{\rho u_0^2/2g} \tag{7.1}$$

where u_0 is the velocity of the approaching stream (by assumption u_0 is constant over the projected area).

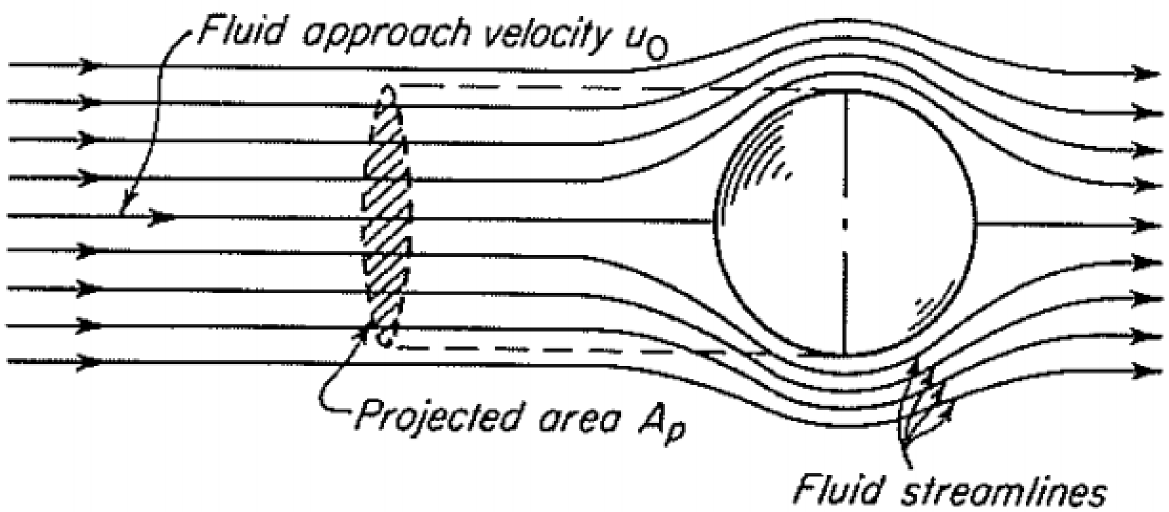


FIGURE 7.2
Flow past immersed sphere.

From dimensional analysis, the drag coefficient of a smooth solid in an incompressible fluid depends upon a Reynolds number and the necessary shape

factors. For a given shape

$$C_D = \phi(N_{\mathrm{Re},p})$$

The Reynolds number for a particle in a fluid is defined as

$$N_{\mathrm{Re},p} \equiv \frac{G_0 D_p}{\mu}$$

where D_p = characteristic length
$G_0 = u_0 \rho$

Stokes law

For low Reynolds numbers the drag force for a sphere conforms to a theoretical equation called *Stokes' law*, which may be written

$$F_D = 3\pi \frac{\mu u_0 D_p}{g_c} \tag{7.3}$$

From Eq. (7.3), the drag coefficient predicted by Stokes' law, using Eq. (7.1), is

$$C_D = \frac{24}{N_{\mathrm{Re},p}} \tag{7.4}$$

In theory, Stokes' law is valid only when $N_{\mathrm{Re},p}$ is considerably less than unity. Practically, as shown by the left-hand portion of the graph of Fig. 7.3, Eqs.

Creeping flow

At the low velocities at which the law is valid, the sphere moves through the fluid by deforming it. The wall shear is the result of viscous forces only, and inertial forces are negligible. The motion of the sphere affects the fluid at considerable distances from the body, and if there is a solid wall within 20 or 30 diameters of the sphere, Stokes' law must be corrected for the wall effect. The type of flow treated in this law is called *creeping flow*.

Fluidization & its applications

- Fluidization is a process in which solids are caused to behave like a fluid by blowing gas or liquid upwards through the solid-filled vessel/reactor.
- Fluidization is widely used in commercial operations; the applications can be roughly divided into two categories, i.e.,
  - physical operations, such as transportation, heating, absorption, mixing of fine powder, etc. and
  - chemical operations, such as reactions of gases on solid catalysts and reactions of solids with gases etc.
- The fluidized bed is one of the best known contacting methods used in the processing industry, for instance in oil refinery plants.
- Among its chief advantages are that the particles are well mixed leading to low temperature gradients, they are suitable for both small and large scale operations and they allow continuous processing.

Fluidization & its applications

- There are many well established operations that utilize this technology, including cracking and reforming of hydrocarbons, coal carbonization and gasification, ore roasting, Fisher-Tropsch synthesis, coking, aluminium production, melamine production, and coating preparations.
- The application of fluidization is also well recognized in nuclear engineering as a unit operation for example, in uranium extraction, nuclear fuel fabrication, reprocessing of fuel and waste disposal.

Fluidization Regimes

When the solid particles are fluidized, the fluidized bed behaves differently as velocity, gas and solid properties are varied. It has become evident that there are number of regimes of fluidization, as shown in Figure 1.

When the flow of a gas passed through a bed of particles is increased continually, a few vibrate, but still within the same height as the bed at rest. This is called a fixed bed **(Figure 1A).**

With increasing gas velocity, a point is reached where the drag force imparted by the upward moving gas equals the weight of the particles, and the voidage of the bed increases slightly: this is the onset of fluidization and is called minimum fluidization **(Figure 1B)** with a corresponding minimum fluidization velocity, U_{mf}.

Increasing the gas flow further, the formation of fluidization bubbles sets in. At this point, a bubbling fluidized bed occurs as shown **in Figure 1C**.

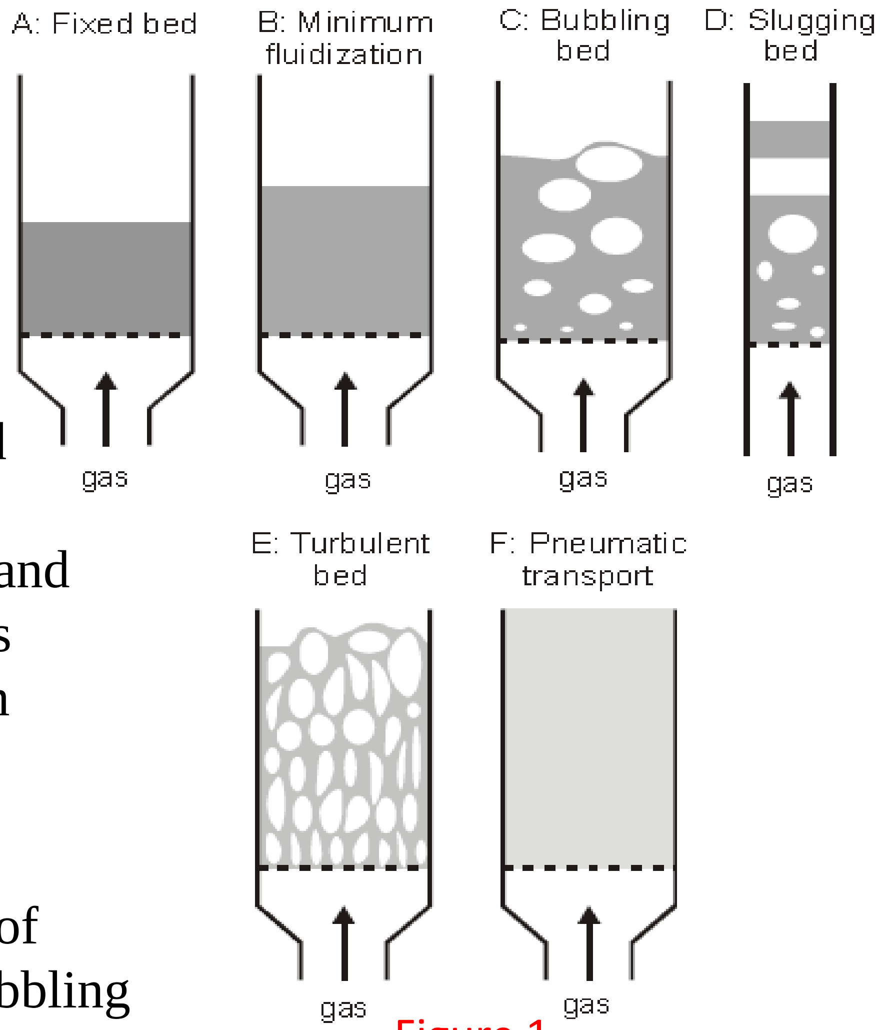
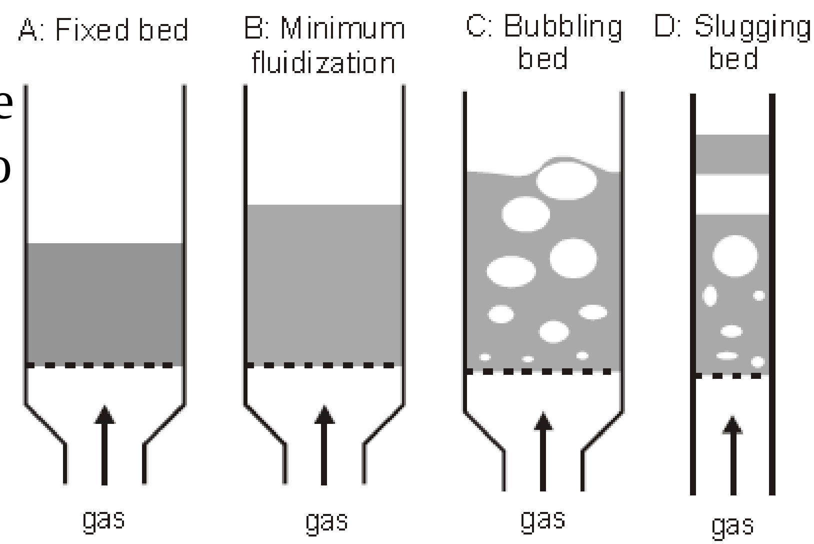
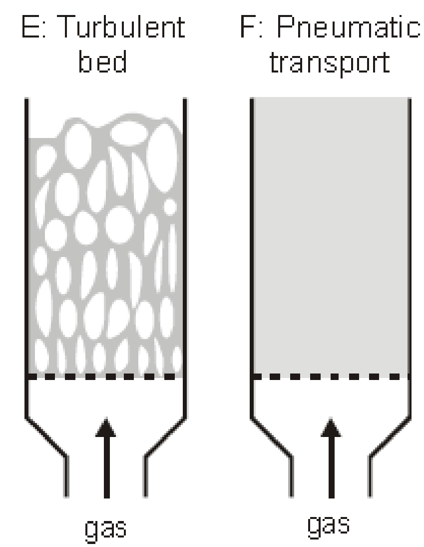


Figure 1.

As the velocity is increased further still, the bubbles in a bubbling fluidized bed will coalesce and grow as they rise. If the ratio of the height to the diameter of the bed is high enough, the size of bubbles may become almost the same as diameter of the bed. This is called slugging **(Figure 1D).**



If the particles are fluidized at a high enough gas flow rate, the velocity exceeds the terminal velocity of the particles. The upper surface of the bed disappears and, instead of bubbles, one observes a turbulent motion of solid clusters and voids of gas of various sizes and shapes. Beds under these conditions are called turbulent beds as shown in **Figure 1E.**



With further increases of gas velocity, eventually the fluidized bed becomes an entrained bed in which we have disperse, dilute or lean phase fluidized bed, which amounts to pneumatic transport of solids. **(figure 1F)**

Effect of fluid velocity on pressure gradient and pressure drop

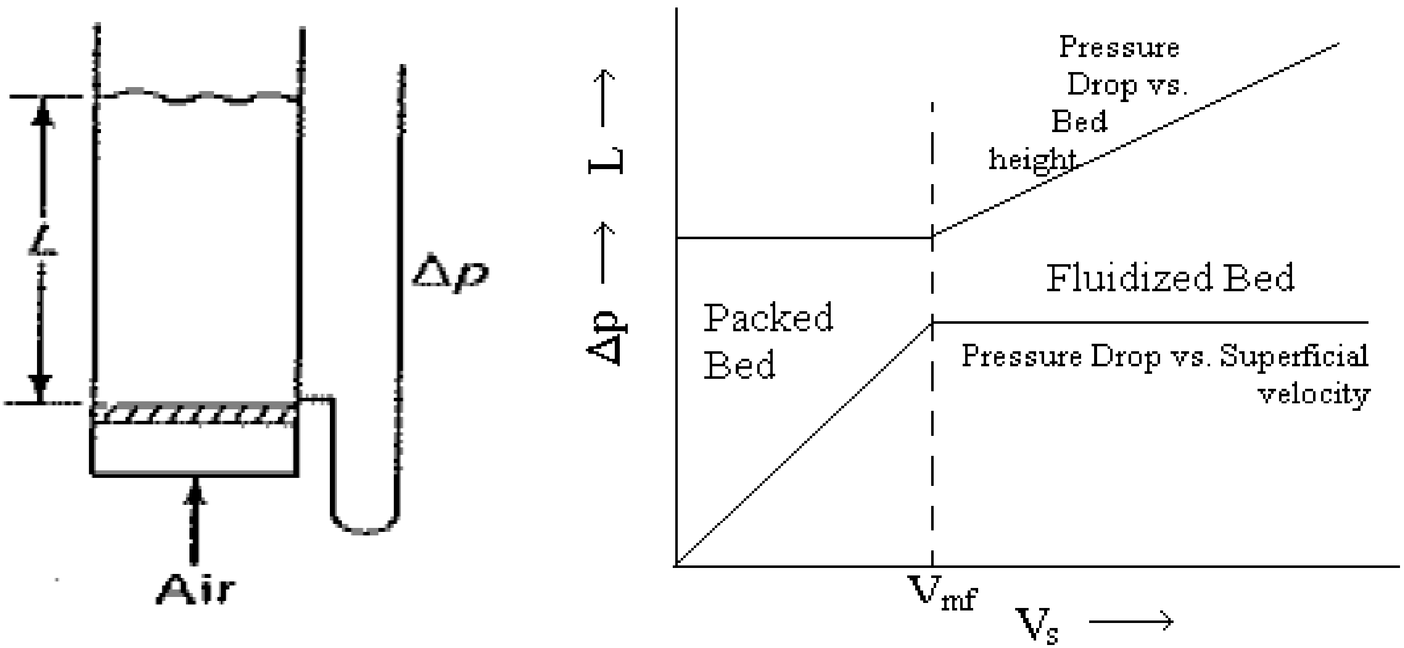


Figure-3: Transition from packed bed to fluidised bed.

Effect of fluid velocity on pressure gradient and pressure drop

- Consider a vertical tube partly filled with a fine granular material such as catalytic cracking catalyst as shown in figure 3. The tube is open at the top and has a porous plate at the bottom to support the bed of catalyst and to distribute the flow uniformly over the entire cross section. Air is admitted below the distributor plate at a low flow rate and passes upward through the bed without causing any particle motion. If the particles are quite small, flow in the channels between the particles will be laminar and the pressure drop across the bed will be proportional to the superficial velocity, V_S. As the velocity is gradually increased, the pressure drop increases but the particles do not move and the height remains the same.
- With further increasing V_S, e may increase and hold Dp constant (L will also increase but its effect is much less than the effect of change in e. The experimental result for such a test is shown in figure.3.
- For velocities less than the minimum fluidization velocity V_{mf}, the bed behaves as a packed bed. However as the velocity is increased past V_{mf}, not only does the bed expand (L increases), but also the particles move apart, and e also increases to keep the Dp constant.
- As the velocity is further increased, the bed become more and more expanded, and the solid content becomes more and more dilute. Finally, the velocity becomes as large as terminal settling velocity V_t of the individual particles, so the particles are blown out of the system. Thus the velocity range for which a fluidized bed can exist is from V_{mf} to V_t.

Types of fluidization

In fluidized bed, Beyond the minimum fluidization velocity V_{mf}, the appearance of beds with liquids or gases is quite different.

During the fluidization, the particles move further apart and their motion becomes more vigorous as the velocity is increased, but the bed density at a given velocity is same in all sections of the bed. This is called ***particulate fluidization*** and is characterized by a large but uniform expansion of the bed at high velocities. It is generally observed with liquid phase as fluidizing media (example: Fluidizing sand with water).

Beds of Solids fluidized with air generally exhibits aggregative or bubbling fluidization. Beyond minimum fluidization velocity, a major portion of gas passes through voids in bed free of solids and only a small fraction of gas flows in the channels between the particles . The particles move erratically along with fluid – but in space between the bubbles i.e void fraction in fluidized bed is same as that at incipient fluidization

Types of fluidization…continue

The non-uniform nature of the bed first attributed to aggregation of particles and termed as **Aggregative Fluidization**; but there is no evidence that the particles stick together and the term **bubbling fluidization** is a better description of the phenomena.

The bubbles that form behave much like air bubbles in water or bubbles of vapour in a boiling liquid, and the **term boiling bed** is sometimes applied to this type of fluidization.

The generalization that liquids give particulate fluidization of the solids; while, gases give bubbling fluidization is not completely valid. The density difference is an important parameter and very heavy solids may exhibit bubbling fluidization with water, while gases at high pressures may give particulate fluidization of fine solids. Also, fine solids of moderate density, such as cracking catalysts, may exhibit particulate fluidization for a limited range of velocities and then bubbling fluidization at high velocities.

Applications of fluidization:

- Important application – Petroleum industry in catalytic cracking
- Fluidized bed combustion of coal – lesser pollutant emissions
- Roasting ores, drying fine solids, energy production.
- Vigorous agitation ensures proper heat & mass transfer
- Turbulent fluidization can ensure proper contact between two phases improving performance of the system.
- Transportation of solids by continuous fluidization
- Hydraulic or slurry transport
- Pneumatic conveyor