1 Introduction to Multiphase Flows

1.1 Multiphase Flow Phenomena

Multiphase flows are found in abundance in both natural phenomena and industrial processes. Natural phenomena sources include such pathways as migration of deserts by sand storm and distributions of rain/snow/hail by wind. Industrial sources include pneumatic transport of solids, spray operations for surface coating and fire quenching as well as pollution control, solid-waste incineration by fluidized bed combustion, and gas–liquid bubble column reactors. In this section, several examples of multiphase flows will be examined in order to demonstrate the distinctly different transport patterns of each phase in the illustrated multiphase flow case. It is also intended to show the naturally caused or intentionally designed consequences resulting from such a difference in phase transport or flow pattern.

1.1.1 Sedimentation in a Particulate Flow

Typically initiated and maintained by a surrounding flow, sedimentation is a phenomenon describing the settling of particulate matter by gravity from the original state of suspension. For example, consider the migration of sand dunes by a strong wind as an illustration of this process. As shown in Figure 1.1-1, the blowing wind mobilizes and even lifts the sand particles from the wind front edge of the sand dune. The airborne sand is carried by wind until gravity intervenes to settle the sands some distance downstream of the wind. Some of the sand in the windward (wake region) may also be disturbed and mobilized by the wake flow. As the shaded layer of wind front resettles into the windward region, the sand dune proceeds to migrate downstream of the wind. Bear in mind that the flow pattern, or transport, of airborne sand is distinctively different from the moving air. Similar patterns may also be observed in sand sedimentation in a strong sand storm. In a strong turbulent wind, the sand stays airborne until the gravity force overpowers the wind's lifting force; this occurs when local wind strength is weakened by flow dispersion (or redistribution) by surface obstructions such as forest or city buildings.

Sand beach is another possible consequence of sand sedimentation dispersal; this phenomenon occurs when sand and fine gravel are carried and deposited by ocean waves brushing the bank, as illustrated by Figure 1.1-2. The waves work to help carry sand toward the bank, and the waves also help carry sand back out to sea when they

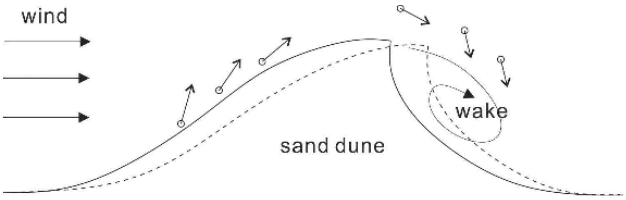


Figure 1.1-1 Migration of sand dune by wind.

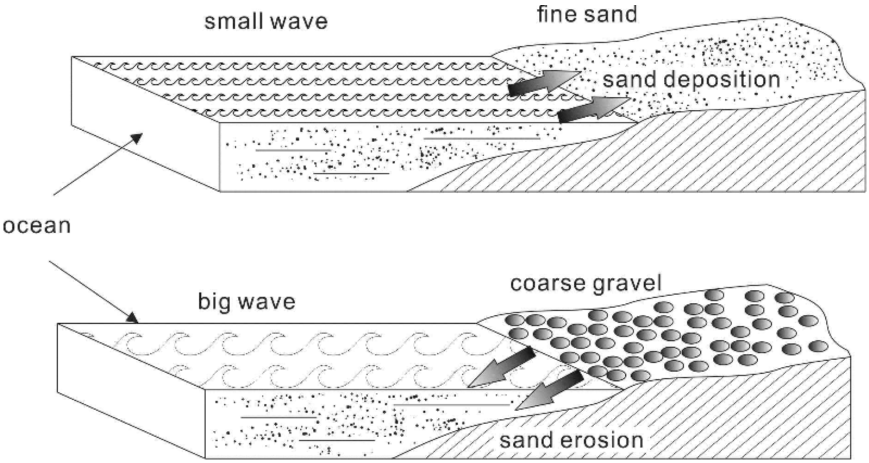


Figure 1.1-2 Sedimentation and erosion on beach by ocean waves.

recede. For that reason, large waves are constantly causing the erosion of the coastal bank and morphological changes of the coastline sand, especially during an ocean storm or hurricane. Thus, the transport (or sediment) of sand by waves depends upon the nature of wave flows as well as their interactions with sands, irrespective of the changes caused by gravity.

Sedimentation principles are also often applied to the design and applications of engineering devices. Figure 1.1-3 shows a particle size selector demonstrating gravitational settling. The mixture of various-sized particles is fed through a hopper and then propelled into the air by a powerful air blower. As the particles are projected into the air, initial momentum is obtained via the air jet. As the air jet flow is quickly dispersed, the particles begin to settle through gravity, with different inertia and particle-flow interactions that are mostly size based, assuming that all of the particles are composed of the same materials. The coarse particles settle nearest to the injection site, and the fine particles settle the farthest away. The ultrafine particles may remain airborne and may be carried away out of the collection zone by the ambient wind or dispersed air flow.

Sedimentation can also be achieved by employing other body forces besides gravity, such as centrifugal forces and electrostatic forces. A tangential-inlet cyclone represents the type of devices used for centrifugal separation, or sedimentation of

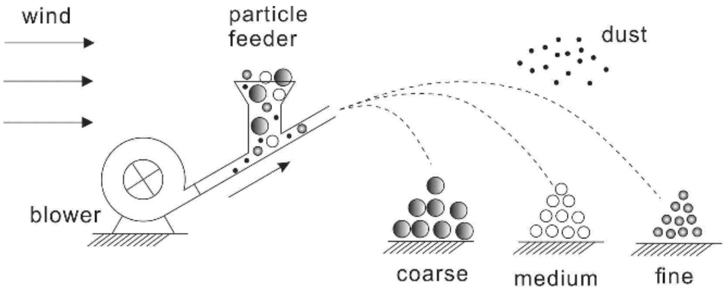


Figure 1.1-3 Particle sizing device by gravitational settling.

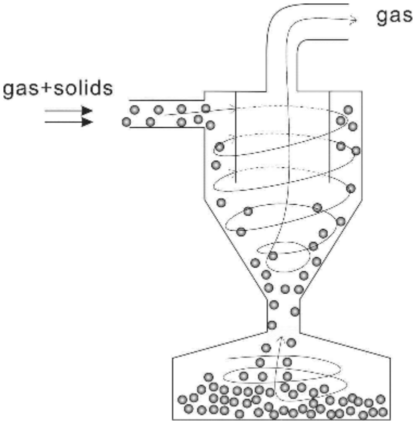


Figure 1.1-4 Cyclone separation of solids.

solid particles, from their carrying air flow. As depicted in Figure 1.1-4, the air flow first forms a tornado-like rotating core inside the cyclone and then leaves the cyclone through the exit. Under the action of the rotating core, the solid particles are subjected to centrifugal force. The centrifugal force then drives the radially migrating particles toward the cyclone wall, while the drag force tends to carry the particles along with the exiting air flow. Since the centrifugal force is proportional to the mass, whereas the drag force is proportional to the surface area, the centrifugal effect of separation is more significant for larger particles than smaller ones. Thus, larger-size particles tend to more easily reach the cyclone wall during their time within the cyclone. When the particle–wall collisions occur, most of those particles lose their momentum and are then trapped in the boundary layer of the wall where air velocity is too low to provide drag forces against the gravity. Hence, the particles on the wall will begin descending along the wall to the collection bunker located at the bottom of the cyclone. The very small and fine particles are unlikely to reach the wall surface during their time in the cyclone, and thus become uncollected and remain airborne in the exiting air flow.

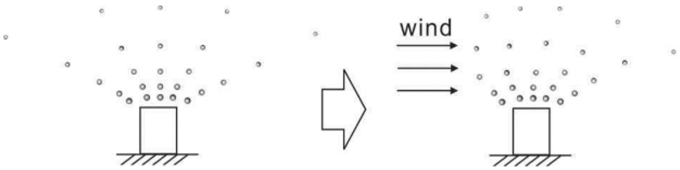


Figure 1.1-5 Wind effect on spray watering from sprinkler.

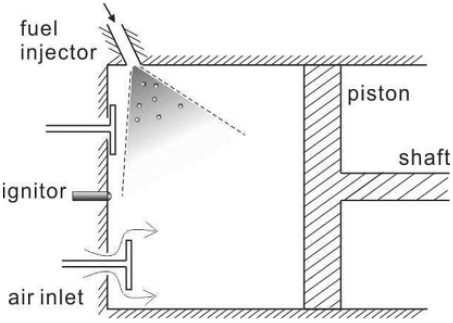


Figure 1.1-6 Fuel injection in engine cylinder.

1.1.2 Dispersion by Sprays or Multiphase Jets

Spray is a common technique for the quick dispersion of droplets or particulate matters. The distribution of sprayed particles is dependent not only upon the properties of injection but also upon the surrounding air flow. Figure 1.1-5 gives an example of the wind effect on sprinkler sprays used for irrigation. Despite the symmetric nature of the liquid spray injection, the droplet deposition on the vegetation becomes asymmetric due to the convective blowing of the wind. In order to obtain a better coverage symmetry, one technically plausible remedy is to adjust the injection angle by tilting the sprinkler toward the wind. Another solution is to adjust the mass flow asymmetrically, with more flow on the wind front side and less on the windward side. In either case, effective adjustment requires knowledge of dynamic interactions between sprayed droplets and wind.

In the form of an atomized spray jet, fuel injection is designed for quick dispersion and vaporization of liquid fuel in many combustion processes, such as hydrocarbon-fuel combustion in automobile engines, as illustrated in Figure 1.1-6. To avoid carbon deposits on the cylinder wall, it may not be desirable to have a direct impingement of liquid fuel spray onto the wall surface of the engine. Therefore, the atomization and injection of the spray needs to be designed with considerations of the hydrodynamic behaviors of droplets and air flow as well as the nature of vaporization and combustion within the engine.

A cooling tower is a device employed in many coal-fired and nuclear power plants and chemical plants, commonly used for thermal energy removal via evaporative water cooling or air cooling of a flow stream in a process. As shown in Figure 1.1-7, a

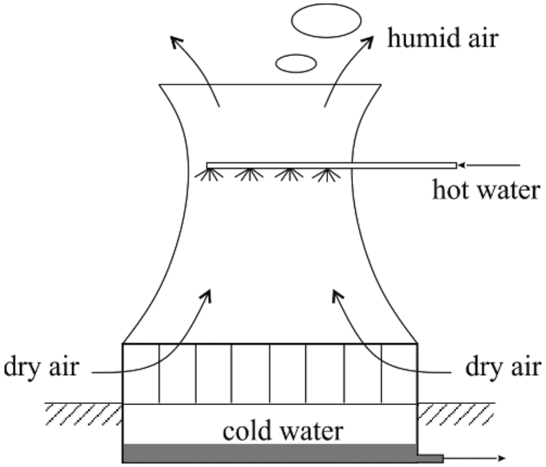


Figure 1.1-7 Sprays in cooling tower.

cooling tower is used to lower the temperature of hot water. A relatively dry and cold air flow passes through the cooling tower from bottom to the top, whereas the atomized droplets from sprays settle downward in a counterflow mode, reacting against the upward-moving gas flow. The droplet vaporization increases the air humidity while lowering the temperatures of the remaining droplets via the route of latent heat transfer. Cooling towers are also used for the pollution control of airborne particulate and hazardous gases via a wet scrubbing process. The absorption of hazardous gases by the atomized droplets consequently reduces the pollution level of exhaust gas. In addition, the airborne particulates are washed away by attaching to the droplets through particle–droplet collisions, thus forming a slurry flow at the bottom of the cooling tower, in a process known as wet scrubbing.

Spray is also commonly used to spread a thin coating layer (typically a polymeric thin film) onto a targeted surface, as shown in Figure 1.1-8. The polymeric liquid (or slurry) is atomized into fine droplets and injected into the air by aerated spray jets. While the gaseous component of the jets is quickly dispersed and merged into ambient air, the droplets, with most of the initial momentum preserved, adhere to the target surface. The coating is formed by the surface drying of the spread droplets attached to the surface. Note that a spray set at an incorrectly high jetting velocity may cause some adverse effects to the smoothness of the coating, such as a rebound of droplets from the target surface or an uneven surface coating.

A sand blaster has characteristics of multiphase flow similar to those of spray coating. Instead of the droplet attachment seen in surface coating, a sand blaster is designed for surface cleaning, in which a spray jet of abrasive sands with high momentum makes a direct impingement onto a cleaning surface, as shown in Figure 1.1-9. The sand particles gain their momentum from the assisting air jet. While the air jet is quickly dispersed and loses its momentum, the sands, with much higher inertia, continue their journey with most of the initial momentum preserved until the

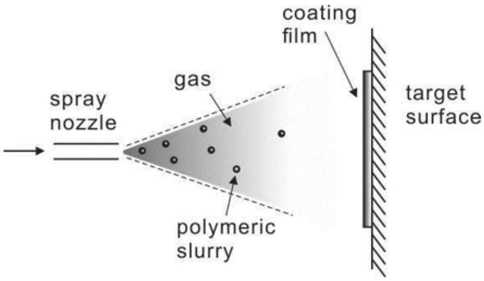


Figure 1.1-8 Spray coating.

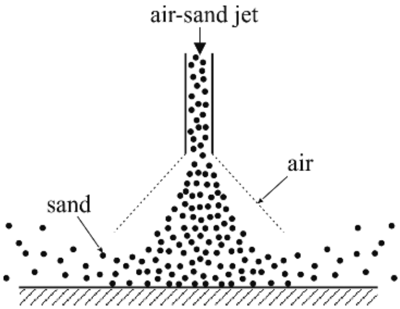


Figure 1.1-9 Sand blasting.

impingement target is reached. After the collisions of abrasive sands and targeted surface, both sand residues and chipped-off bits of surface material may become airborne and dispersed again by the air jets as they reach the surface.

1.1.3 Mixing and Material Processing

The mixing of solids and liquids is an important aspect of applications involving multiphase flow. Figure 1.1-10 shows an industrial device for concrete mixing. The mixture of cement, gravel, and water is combined by rotational stirring within a cylindrical chamber. In this case, the aggregate of each phase may initially exhibit a different dynamic response to the rotational agitation. As the mixing operation progresses, the chemical bonding formation among the cement and water makes the mixture and gravel appear as a paste-like slurry in which the difference in each component's flow dynamic responses eventually disappear.

Mixing can also be achieved via rotational agitation by applying rotating blades in a stirred tank, as shown in Figure 1.1-11. In the case of slurry mixing, the blade's rotational movement agitates the liquid to generate a vortex core that engulfs the surrounding particles into spiral motions, along with the rotating fluid. In the case of dry mixing or blending, the rotating blades cause the movement of dry particles by direct collisions between the blade and particles as well as among the particles themselves. The air in the stirred tank of dry mixing also begins flowing as a result

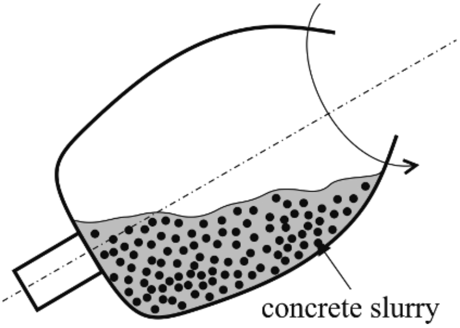
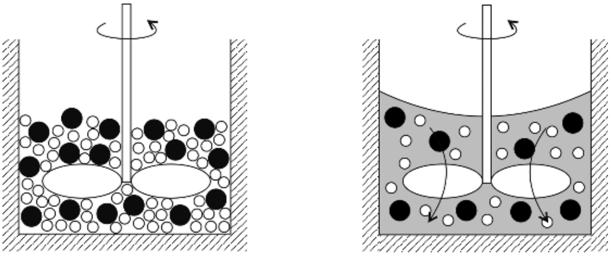


Figure 1.1-10 Concrete mixing.



(a) dry mixing (b) slurry mixing

Figure 1.1-11 Mixing in blade-stirring tanks.

of the blade's agitation and particle movement. Consequently, in terms of uniformity in particle size and concentration distributions, the mixing quality in a stirred tank depends upon the particle-related coupling among the dynamic motions of fluid, blades, and particles.

Mixing of granular particles can also be achieved by gas fluidization, as shown in Figure 1.1-12. The fluidizing gas moves upward to suspend and mobilize the particles. The gas bubbles, or voids, are typically distinguishable in the dense suspension, as their wobbly movement through the bed further agitates the suspended particles. When the gas passes through the bed, the particles (suspended at a moderate gas velocity) remain inside the bed, with in-bed recirculation and many collisions among and between the particles and the bed wall. Typical examples of the types of applications for this process include fluidized bed combustors for coal-fired boilers, and catalytic fluidized bed reactors for chemical synthesis.

Figure 1.1-13 illustrates a three-phase fluidized bed used as a chemical reactor whereby the gaseous reactants, in the form of bubbles rising through the bed, react with the liquid reactants in the presence of solid particles, which function as catalysts. The rising bubbles carry a certain amount of liquids or liquid–solid in the wake regions. The transport phenomena in the bed are strongly affected by the wake and wake shedding behavior, which establishes a circulatory liquid or liquid–solid flow pattern in the bed. When the particle size is small, the reactor is known as a slurry

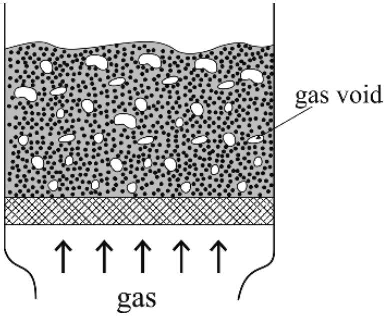


Figure 1.1-12 Gas–solid fluidized bed.

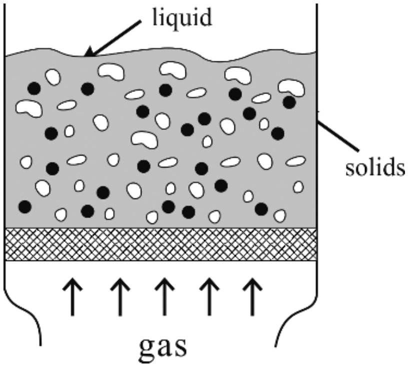


Figure 1.1-13 Gas–liquid–solid three-phase fluidized bed.

bubble column for which the liquid–solid mixture or the slurry remains within the reactor and gas flows in and out of the reactor.

The storage of granular food, such as beans and wheat grains, constantly requires drying to remove the excessive moisture. A spouting bed is a typical type of device for such a drying operation, as illustrated in Figure 1.1-14. Most granular food particles are just too big and heavy to be fully or uniformly fluidized; rather, they are merely lifted by the drying gas jet and then quickly settle down by gravity once the jet disperses to form a spouting among the surrounding particle cloud. The jet entrainment at the bed bottom introduces new particles, and the completely dried particles may be flushed out of the bed because they become lighter through a loss of moisture. The magnitude of the drying effect depends upon the multiphase flow characteristics, which includes the rate of solids recirculation between the spout and annulus regions as well as the contact time between the gas and food particles.

Jet milling is a process used to break large-sized particles or particle agglomerates into smaller fragments via the head-on collision of particles, in a process that is assisted by a pair of opposite particle-laden jets, as shown in Figure 1.1-15. The damaged fragments may be further broken down by an additional attrition method, such as grinding, and the attrited bits are removed along with the exit gas streams.

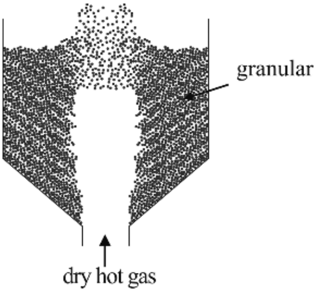


Figure 1.1-14 Spouting-bed dryer.

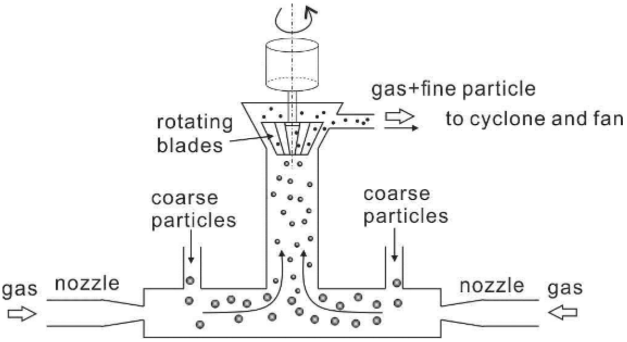


Figure 1.1-15 Jet milling.

1.1.4 Pipeline Transport

Pneumatic conveying is a common means of solids transport, where solid particles are aerated and transported in a pipe or channel from one location to another through gas flowing by using either blowing or suction action. In a horizontal transport, the suspended solids are subjected to both horizontal carrying force (drag force) and gravitational settling force, as shown in Figure 1.1-16. This results in a transport flow pattern that has a sliding layer of dense concentrated solids near the pipe bottom and fast moving particles of a dilute concentration near the top part of the pipe section. The transport flow can become unsteady and wavelike with the increase of solid loading to the flow, and sedimentation of particles and collisions may even form moving dunes.

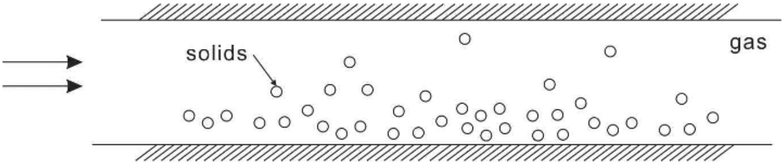


Figure 1.1-16 Pneumatic conveying of solids.

Similar to the way in which the pneumatic conveyance of dry solids is done via gas pipe flows, the solid particles can also be transported by liquid flows through pipe lines such as sewage drainage pipes or offshore crude oil transport pipelines, as shown in Figure 1.1-17. In a slurry pipe flow, the slurry may not fill the entire pipe cross-section all the time, leaving a void space of gas, thus creating an interface between the gas and slurry. Therefore, a slurry pipe flow transport may involve motions of gas, solids, and liquids, with a wave-free surface between the gas and slurry.

There are many types of multiphase flows through vertical pipes. Riser flows in a reactor system represent typical vertical pipe flows in which both fluid and particles are transported upward against the force of gravity, as shown in Figure 1.1-18. One example of riser flow application is the fluidized catalytic cracking (FCC) process seen in petroleum oil refineries, from which most gasoline, diesel, and heating oils are produced. In a FCC process, the feed stock vapor interacts with the catalytic solids alongside their transport in the riser. The subsequent catalytic reaction cracks the heavier molecular feed into low-molecular-weight fuels resulting in the booming of gas velocity with an increased number of moles and volume. This response changes not only the transport flow pattern of nonreaction but also the cracking itself,

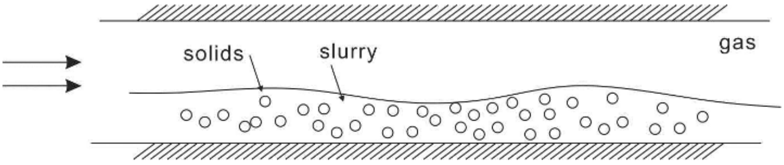


Figure 1.1-17 Slurry pipe flow.

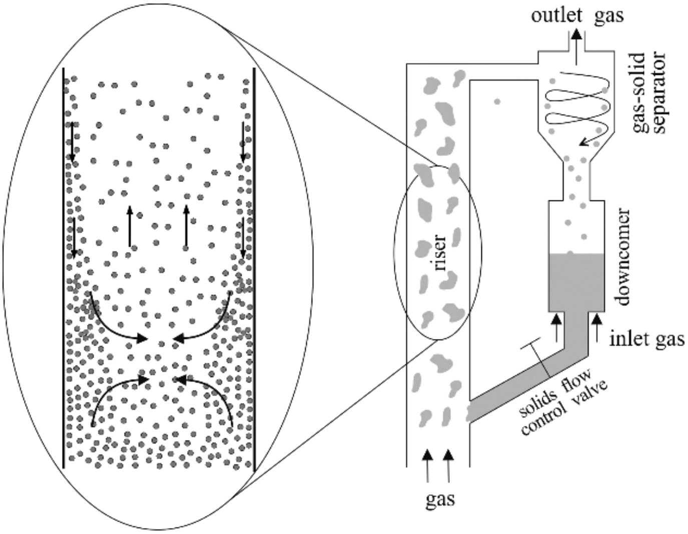


Figure 1.1-18 Riser flow in a circulating fluidized system.

due to the changes in contact time and temperature between feed vapor and catalysts, as well as the change in the local volumetric concentration of catalysts.

1.1.5 Flows with Charged Particles

In flows of dry granular materials, the solid particles become electrostatically charged via either collisions or by electric fields. Laser printing is a typical example of the controlled deposition of particles (toner) in an electric field, as shown in Figure 1.1-19. The printing cycle starts from charging the rotating photosensitive drum and exposing it with image information from laser beam. The particles are fed by a roller under a funnel-shape toner, and picked up by the charged drum. Via another corona transfer, these well-patterned particles then deposit onto the paper. The particle flow is mainly subjected to gravity force in the hopper, while dominated by electric force only during the remainder of the process.

Another example of this type of process is that of electrostatic precipitation for aerosol removal from aerosol-laden gas flows, as shown in Figure 1.1-20. In these cases, the particles suspended in a gas stream are first charged by a corona charger. Next, the charged particles are separated from the gas stream by an external electric

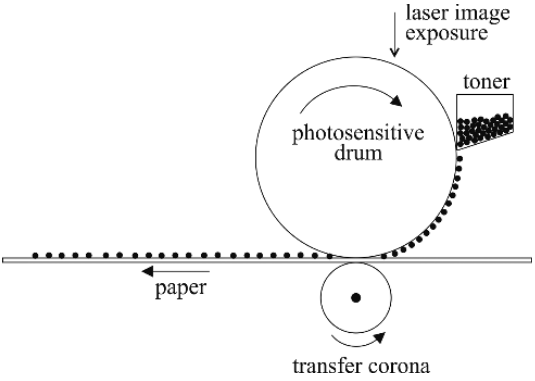


Figure 1.1-19 Laser printing with dry toner.

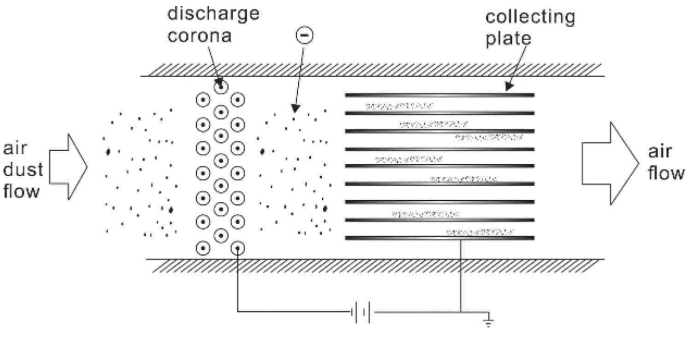


Figure 1.1-20 Electrostatic precipitator.

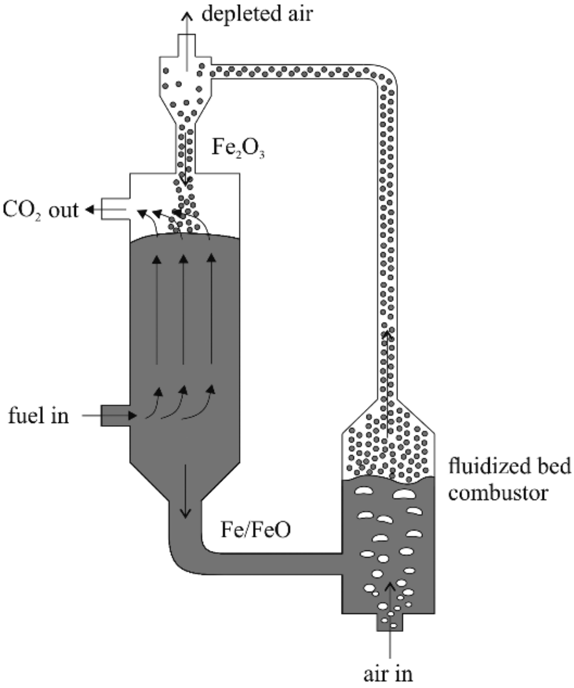


Figure 1.1-21 Chemical looping reactors.

field in which electric forces drive the particles toward the collectors. In addition to the electric force, the particle motion is also affected by the hydrodynamic force as well as other forces, such as gravity.

1.1.6 Flows with Chemical Reactions

In the flows of metal oxide oxygen carrier particles represented by iron oxides in the chemical looping reactor system as given in Figure 1.1-21, the fully oxidized iron oxide particles regenerated from a fluidized bed combustor are transported through a riser to a moving bed reducer after a cyclone separation of the oxygen-depleted air from the riser flow stream (Fan, 2010; 2017). The fully oxidized iron oxide particles are then reduced after reacting with the carbonaceous fuels introduced to the moving bed. The reduced particles from the moving bed are then transported through an L-valve to the combustor for regeneration. The reduction–oxidation reactions take place at high temperatures (*e.g.*, higher than 900°C) and can be at high pressures (*e.g.*, about 10 atm).

Several flow regimes are involved in this particle circulatory loop system including bubbling or turbulent fluidization regime for the combustor operation, fast fluidization regime for the riser flow, moving bed flows for the reducer, and vertical moving bed and dense horizontal transport for the L-valve. Gas aeration to the L-valve is used to control the particle flow rate in the nonmechanical valve setting.

Fines can be generated from attrition due to the particle stresses induced by both the flow and the chemical reactions. The cyclone is designed also to separate the attrited particles.

1.2 Definition of Multiphase Flow

The main characteristics of a multiphase flow include distinctively different dynamic responses of each phase and strong phase interactions that impact the transport phenomena. Hence it is essential to understand the differences between a multiphase flow and a multicomponent single-phase flow, as well as the differences between a dense-phase multiphase flow and a dilute-phase multiphase flow.

1.2.1 Multiphase Flows versus Multicomponent Flows

Multiphase flow is a term commonly used to refer to a type of flow that involves more than one physical state of the medium (*i.e.*, gas, liquid, or solid phase). Multiphase flow can also describe a flow where the flow media present in the flow field exhibits different dynamic behaviors when subjected to a particular driving force (Soo, 1965). To illustrate the dynamic phases involved in these processes, consider a situation in which the wind blows over a pile of fine dust, granular sand, and large rock. The fine dust will be easily airborne or suspended in the wind; the granular sand may be partially blown off and quickly resettled by gravity, and the large rocks typically remain stationary. In this particular situation, just using the term “solid phase” to describe the three types of distinctively different dynamic response behaviors of solid particles from the blowing wind will be inadequate. This is especially true when considering a consequent analysis of the transport mechanisms and mathematical modeling involved in a multiphase flow system. Therefore, in this book, a phase will be defined based on the medium dynamic response characteristics that are present, rather than just the physical state of the medium.

With the different dynamic responses of the phases, the interactions among the different phases will occur through their common interface. Such interactions may include various forms of momentum transfer (such as drag force and collision force), energy transfer (such as conductive and convective heat transfer), charge transfer (such as collision-induced electrification), and mass transfer (such as evaporation, reaction, and attrition). It is noted that a dynamic phase may contain multiple components or chemical species. Interactions can also take place between the various components through either diffusion or chemical reactions. However, bear in mind that there is no distinct boundary between the components. For example, for an evaporating fuel spray of bidispersed droplets that are injected into an air-filled combustor, there are three distinctive dynamic phases involved in the transport process: gas mixture phase, droplet phase of small droplets, and droplet phase of large droplets. The gas mixture phase is a multicomponent phase that consists of such gaseous components as fuel vapor, oxygen, and nitrogen.

Many multiphase flows have a continuous spectrum in their dynamic responses, which theoretically would require identification of an infinite number of phase groups to fully describe the multiphase transport properties. One example is that of a sand storm, in which the size distribution of sand particles is continuous over a wide range, varying in size from submicron to a few millimeters. In this instance, a finite number of lumped phases can be introduced to represent groups of particles with similar dynamic responses, as characterized by their averaged property. The exact number of the lumped phases depends on the particular tolerance level that is acceptable to the applications of interest.

1.2.2 Dilute Phase versus Dense Phase

In a multiphase flow, at least one phase is a continuum fluid, such as gas or liquid, which typically functions as a carrying medium for the phase transport. The other phases are usually composed of various rigid particles, such as solid particulates, or deformable particles such as droplets and bubbles. These particles interact with each other by either modifying the flow field, thereby indirectly influencing the hydrodynamic forces, or directly affecting their dynamics through collision or by endured contact. The particles may also interact through other mechanisms, such as electrostatic forces or colloidal forces. Depending on the nature and effective range of the particle–particle interactions that are of interest, the particle phase can be categorized into dilute and dense phases. A dilute phase refers to a particle phase in which the interactions among those constitutive particles are so insignificant (compared to the interaction between the carrying fluid and particles) that they can be ignored in the mechanism analysis and modeling of the phase transport. In contrast, a dense phase refers to a particle phase where the interactions among the constitutive particles play an important role in the phase transport. Particle–particle interactions in a dense phase can be divided into two interaction modes: noncontact interaction, by which the particles affect each other indirectly via the fluid–particle interactions or via noncontact mechanisms such as charge interactions, and contact interaction, in which interactions take place directly through the contact interface between particles.

The demarcation between the dilute and dense phases is usually based on the consideration of hydrodynamic interactions. In this case, the demarcation can be conveniently estimated based on the relative interparticle distance, which is the ratio of the distance to particle size, or it can be equivalently based on the particle volumetric fraction of that phase. For instance, a particle phase in a typical turbulent flow transport can be regarded as a dilute phase when the particle volume fraction is less than 10^{-6}. A particle phase in a laminar flow transport may be regarded as a dilute phase when the particle volume fraction is less than 10^{-4}. When the particle volume fraction is higher than 10^{-2}, the contact interaction becomes more important. It should be noted that when a long-range interaction is involved, such as the electrostatic interactions between charged particles in a suspension flow or the thermal irradiation among molten metallic particles in a reactor, the demarcation between dilute and dense phases can be quite different from that defined only from the hydrodynamics perspective.

1.3 Modeling Approaches

In the modeling theory of multiphase flows, the basic approaches can be roughly divided into two categories. The first category, known as the Eulerian–Lagrangian modeling, looks at fluid motion and the dynamics of particle phases in a particle trajectory-tracking frame. The second category, known as the Eulerian–Eulerian modeling, describes a fixed space domain filled with a pseudo-continuum of the particles. In both approaches, the dynamics of the actual continuum fluid phase is typically described as an Eulerian model similar to that for a single-phase fluid dynamics but modified by interactions with particles.

1.3.1 Eulerian–Lagrangian Modeling

Tracking the dynamic behaviors of each individual particle in a multiphase flow is an intuitive choice among various modeling options. This is due to the merits of the convenient revelation of actual phase transport and the direct application of physical laws that govern the particle transport. The Lagrangian trajectory modeling also poses a significant advantage in using the mathematical formulation of governing equations. The transport equations of each particle are expressed by a set of ordinary differential equations in their Lagrangian coordinates and hence can be readily solved using numerical methods such as the Runge–Kutta algorithms.

Typical Lagrangian approaches to be used include the deterministic trajectory method and the stochastic trajectory method; other methods include the probability-density-function (PDF) based trajectory method and the discrete element method (DEM). The deterministic trajectory method disregards all randomness involved in the particle transport, particularly the random nature of the turbulent flow to which the particle is exposed. The stochastic trajectory method takes into account the randomness that is in the turbulent flow, along with other random effects, such as the initial conditions of the particle's motion. To obtain the statistic average over such randomness, statistical computations covering a large number of possibilities for the same particle need to be performed, by the use of various techniques, such as the Monte Carlo method. Alternatively, a probability-density-function method can be introduced to tailor the randomness involved in the action. Such an approach would require the predetermination of the random nature of the stochastic process, along with the coupling with the deterministic transport equations. The DEM model, also known as the soft-sphere model, handles the type of cases where the detailed contact transfer among interparticle collisions is important. The collision dynamics in a DEM model is based on the analogy to the spring-dashpot-slider modes for normal impact, tangential, and rotation contact, with or without sliding. All of the above mentioned trajectory models for particle motion are coupled with models for the continuum fluid flow in which the particles are exposed or suspended.

The development of Lagrangian models has been limited mainly by the inherent need for the large computing capacity capable of tracking each particle in the system, to conduct statistic averaging over the randomness, and the need to compute various interactions with other phases, system boundaries, and particles of the same phase. In practice, the applications of Eulerian–Lagrangian modeling are focused on the dilute transport cases, where multi-continuum approaches may not be appropriate, or in cases in which the temporal tracking of particles is important, such as in spray drying of slurry droplets in a furnace or the tracking of radioactive particles in a particulate flow.

1.3.2 Eulerian–Eulerian Modeling

The performance of a multiphase flow system constantly calls for the microscopic "field" descriptions of dynamics of each phase. To this end, the Eulerian–Eulerian description of phase transport is the most convenient option among available modeling choices, as it is a direct extension of the mathematical formulation of fluid dynamics from a continuum single phase fluid, to a multi-continuum multiphase "fluid medium." There are three key issues in this extension: one is the construction of pseudo-continuum of the particle phase(s) that "co-share" the common space of multiple phases or multi-continuum at the same moment; the second is the interphase interactions and transfer among the multi-continuum phases; the final is the transport properties, such as viscosity and diffusivity of each pseudo-continuum, that need to be determined via constitutive equations or correlations of pseudo-continuum variables.

The pseudo-continuum of a particle phase can be established by applying the volume averaging theorems over a control volume. To account for the turbulence effect, the time averaging should be adopted after the volume averaging (Soo, 1989). Since the pseudo-continuum is based on the volume averaging, the pseudo-continuum phase should be regarded as compressible, due to the nonuniform distribution of the phase volume fraction, even if the materials that constitute the phase are incompressible.

In the collision-influenced transport of a dense phase, the modeling of the collision stress of the pseudo-continuum particle phase becomes important. The kinetic theory of granular flows has been developed to account for this collision stress by using the analogy to the molecular kinetic theory of dense gas transport.

1.4 Case Studies: Peculiarities of Multiphase Flows

The following case studies further examine some simple yet interesting phenomena of multiphase flows whose transport mechanisms are hard to be intuitively understood or difficult to be modeled. These discussions are mainly aimed to stimulate readers' interests in learning the multiphase flow theories in the following chapters, rather than to provide a detailed modeling analysis or solution.

1.4.1 Bubble Acceleration

Problem Statement: Consider a small spherical bubble initially at rest in a stagnant liquid column. What is the initial acceleration of the bubble?

Analysis: Considering the steady-state motion of a particle in a fluid, the typical forces acting on the particle include the gravitational force, the buoyancy force, and the drag force. Directly applying these forces to the transient motion of a bubble in a fluid based on the Newton's second law of motion, and if there is a relative motion between the bubble and the fluid, the equation becomes:

$$\rho_b V_b \frac{dU_b}{dt} = (\rho_l - \rho_b) V_b g - C_{Db} A_b (U_b - U)^2. \tag{1.4-1}$$

From Eq. (1.4-1), the initial acceleration can be expressed by:

$$\left.\frac{dU_b}{dt}\right|_{t=0} = \left(\frac{\rho_l}{\rho_b} - 1\right) g. \tag{1.4-2}$$

The acceleration calculated by Eq. (1.4-2) gives rise to about 1,000g (assuming the liquid density is about 1,000 times more than the bubble density). This result, however, is contrary to experimental measurements, which suggests about 2g! What is wrong with the purported solution?

The answer is that additional forces are applied to a bubble when it undergoes an acceleration, deceleration, or transient state of motion including the carried mass force and Basset force (see Section 3.2.2). In this case, with the historical integral in Basset force neglected, the force balance equation of Eq. (1.4-1) is corrected by including the carried mass force as:

$$(\rho_b V_b + C_A \rho_l V_b) \frac{dU_b}{dt} = (\rho_l - \rho_b) V_b g - C_{Db} A_b (U_b - U)^2, \tag{1.4-3}$$

where C_A is a shape factor of carried mass (0.5 for a sphere). Based on Eq. (1.4-3), the bubble's initial acceleration is given by:

$$\left.\frac{dU_b}{dt}\right|_{t=0} = \left(\frac{\rho_l - \rho_b}{C_A \rho_l + \rho_b}\right) g, \tag{1.4-4}$$

which is about 2g since $\rho_l \gg \rho_b$.

Comments: This case analysis shows that, in the modeling of a transient velocity of the disperse phase, one should consider all the major forces acting on the disperse phase, including the carried-mass force in this case, in order to yield the correct velocity prediction.

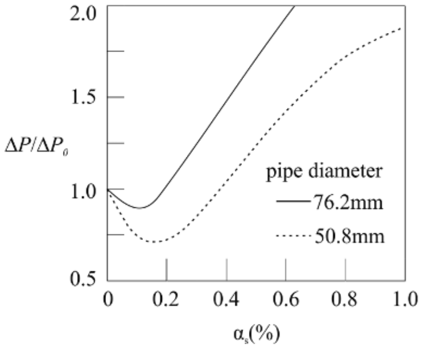


Figure 1.4-1 Pressure drop as a function of solids volume fraction (10µ zinc particle; Pipe Re=53,000, after Shimizu *et al.*, 1978).

1.4.2 Pressure Drop Reduction in Pneumatic Transport

For a fully developed particle-free single-phase turbulent pipe flow, the pressure drop per unit pipe length can be determined by the force balance against the wall friction by:

$$\left.\frac{dP}{dz}\right|_0 = \frac{4}{D}\tau_{w0} = \frac{4}{D}\mu_{T0}\left.\frac{\partial U}{\partial r}\right|_{w0}. \tag{1.4-5}$$

For a pneumatic pipeline transport of dilute particle suspension, the pressure drop per unit pipe length for a fully developed pipe transport flow can be expressed by:

$$\frac{dP}{dz} = \frac{4}{D}(\alpha_w\tau_w + \alpha_{sw}\tau_{sw}) = \frac{4}{D}\alpha_w\mu_T\left.\frac{\partial U}{\partial r}\right|_w + \alpha_{sw}\mu_T\left.\frac{\partial U_s}{\partial r}\right|_w. \tag{1.4-6}$$

In a range of the solids volume fraction at 0.1–0.5%, it is found that the pressure drop can be even smaller than that of particle-free flows under the same flow conditions (by a factor up to 30%), as shown in Figure 1.4-1. This has a clear benefit of energy savings for the pneumatic transport of granular materials.

Problem Statement: It has been experimentally shown that the radial profiles of the gas velocity (with and without dilute particle suspensions) are almost the same, and the solids volume fraction is very small (so the gas volume fraction is almost the same as the particle-free case). However, since the wall friction of solids cannot be negative (based on the physics and factual observations), how does one explain this multiphase flow transport phenomenon?

Analysis: Since the equation stated above represents a scientific fact, there must be an underlying physical mechanism to cause the action. By comparing Eq. (1.4-6) to Eq. (1.4-5), in the transport regime where pressure drop reduction occurs, the following is obtained:

$$\frac{4}{D}\alpha_w\mu_T\left.\frac{\partial U}{\partial r}\right|_w + \alpha_{sw}\mu_T\left.\frac{\partial U_s}{\partial r}\right|_w < \frac{4}{D}\mu_{T0}\left.\frac{\partial U}{\partial r}\right|_{w0}. \tag{1.4-7}$$

Since the solids wall friction must be positive, Eq. (1.4-7) reduces to

$$\frac{4}{D}\alpha_w \mu_T \left.\frac{\partial U}{\partial r}\right|_w \ll \frac{4}{D}\mu_{T0} \left.\frac{\partial U}{\partial r}\right|_{w0}. \tag{1.4-8}$$

Based on experimental findings showing that radial profiles of gas velocity (both with and without dilute particle suspensions) are almost the same and that the gas volume fraction is also almost the same as the particle-free case, the following relationship must be valid:

$$\mu_T \ll \mu_{T0}. \tag{1.4-9}$$

Indeed, the above equation is true due to the turbulence damping effect by the presence of suspended particles leading to a low viscosity (an important phase interaction to be discussed directly in Section 6.7.3).

Comments: This case study shows the analysis that helps direct the discovery of one of the major mechanisms (turbulence modulation) in multiphase flows, through logical progression.

1.4.3 Acceleration of Solids in a Dense Gas–Solid Riser

One puzzling observation in the circulating fluidized bed systems is the acceleration length of solids in a dense gas–solid riser. According to the momentum equation of the particle phase over the cross-section of the riser, it gives:

$$\alpha_s \rho_s U_s \frac{dU_s}{dz} = -\alpha_s \frac{dP}{dz} + F_D - \alpha_s \rho_s g - \frac{4}{D}\tau_{sw}. \tag{1.4-10}$$

The drag force may be correlated to the local multiphase flow properties by the Richardson–Zaki equation as

$$F_D = \frac{18\mu}{d_s^2} \frac{\alpha_s}{(1-\alpha_s)^n}(U - U_s). \tag{1.4-11}$$

Combining the above equations with the continuity equations of solids and governing equations of the gas phase, the velocity distribution of solids along the riser can be solved, as schematically described in Figure 1.4-2.

Problem Statement: Why is the acceleration length of solids from the model prediction always much shorter than the measurements, typically by a factor of two orders of magnitude? What could be wrong with the above modeling?

Analysis: The discrepancy between the model prediction and measurements clearly indicates at least one important governing mechanism is missing, or the quantification of governing equations above is ill-formulated, or possibly both.

The analysis is started by examining the term-by-term comparisons in the major governing equation (*i.e.*, the momentum equation of solids). There are a few important experimental facts that are very useful for this comparison: (1) the pressure drop per unit riser length is much higher than the suspended solids weight; (2) the wall friction is relatively much smaller than other terms, except for risers of very small

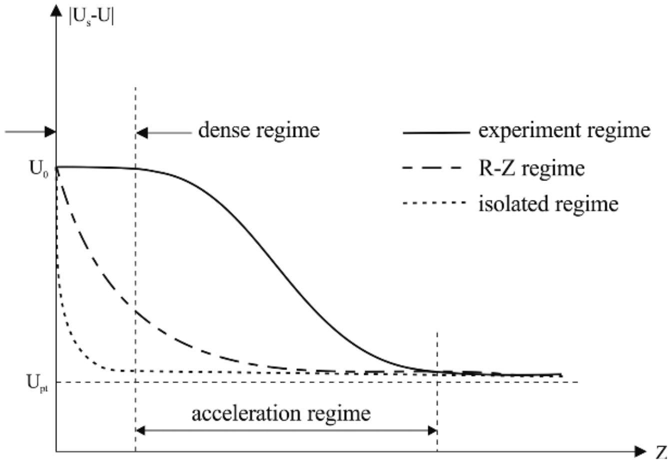


Figure 1.4-2 Solid velocities in a riser: predictions based on a model of isolated particle or Richardson–Zaki equation against experimental results.

column diameters; (3) the gas velocity is much higher than the solids velocity, typically by one to two orders of magnitude; and (4) solids accelerate quite slowly in the dense phase transport region.

Based on the truism of fact three (3), the wall friction effect may be ignored for riser transport of large column diameters (which is true for most industrial riser applications). Fact four (4), indicates that the summation of various momentum contributions on the right-hand side of Eq. (1.4-10) should be small, or basically balanced for the dense phase transport. However, both fact one (1) and fact two (2) show that the combined term would be much higher than the suspended solids weight; hence, it is impossible to balance these three remaining terms. Since the drag force cannot be negative (according to fact two (2)), there has to be another resistant force to counterbalance the rest. This additional resistance to the solids acceleration is supposedly due to the nonequilibrium collisions along the solids transport (Zhu and Wang, 2010).

Comments: This case analysis not only shows the logical path that leads to the discovery of the missing governing mechanisms (nonequilibrium interparticle collision force) in dense gas–solid flows, but also shows the misinterpretations, and hence the great need in the development of multiphase flow theories for engineering applications.

1.4.4 Cluster Formation and Instability

In particulate suspension flows, clusters are constantly formed. Clusters are different from agglomerates. A cluster refers to a loose pack of particles that will be soon dispersed or reorganized, as observed in a riser flow shown in Figure 1.4-3. The

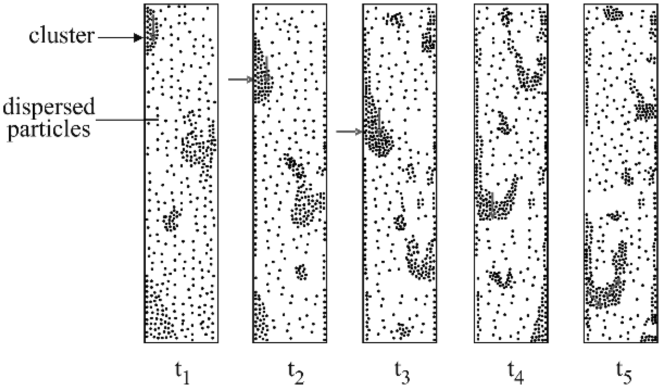


Figure 1.4-3 Schematic diagram of clusters and dispersed primary particles.

cluster is a transient group of interactive particles, with a short lifetime of the group stability.

Problem Statement: What causes the formation of a cluster and the cluster's transient transport behavior?

Analysis: In fast fluidization, particle collisions and particle-turbulence interactions yield high concentrations of solids in the low-velocity wall region. As the solids concentration reaches a certain level, the solids accumulate at various locations on the wall in the form of a cluster. The cluster, identified with arrows in Figure 1.4-3, is of a wavy shape. As it builds up, more particles are moving into the wall region. It moves downward as a result of the net effect of gravitational and drag forces imposed by the flow stream in the core region. When the cluster becomes highly wavy, and the frontal face (leading edge of the layer) becomes bluff; particles in this region are swept away from the wall region in much the same way as turbulent bursts occurring in the boundary layer (Praturi and Brodkey, 1978). The bursting process is quite sudden compared to the growing process. Considerable amounts of solids are entrained from the wall region to the core region during this process. A complete cycle of the evolution of such a cluster is illustrated in Figure 1.4-3. The measurement of local voidage suggests that the large cluster is fragmented into relatively small clusters during the ejection process as a result of large eddies. The bursting causes a surge in the local solids concentration, which in turn enhances the local turbulence. Thus, the bursting phenomenon evolves into a large-scale structure characteristic of the core region, while the flow in the core region affects the frequency of bursting. The existence of the cluster and the event of bursting can be detected from the measurements of the instantaneous local solids concentration variation (Jiang *et al.*, 1993), visualization, or computation (Gidaspow *et al.*, 1989).

It is noted that a cluster as referred to here is a lump of solid particles over which flow properties such as voidage do not vary substantially. It is formed mainly as a result of hydrodynamic effects. The mechanism of particle clustering is different

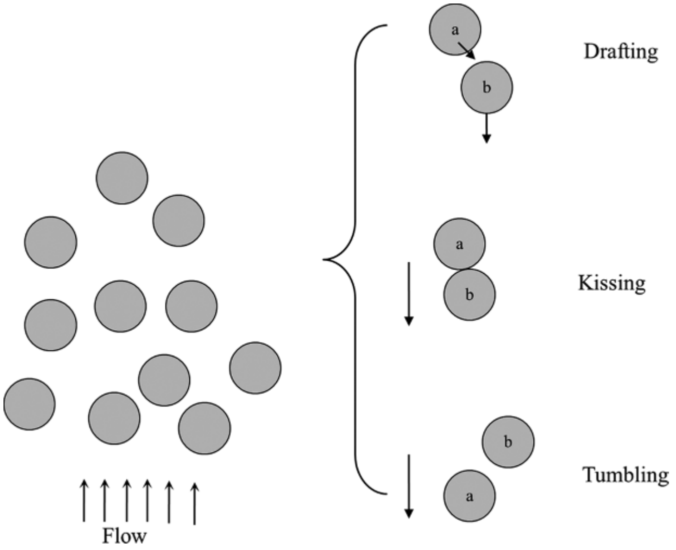


Figure 1.4-4 Transient characteristics of settling particles in a liquid.

from that of agglomeration, in which particles adhere to one another mainly by surface attraction (*i.e.*, van der Waals force and electrostatic forces) and mechanical or chemical interaction (Horio and Clift, 1992).

Comments: This case study illustrates the formation of typical clusters in a riser. It is noted that the formation of clusters alters the large-scale motion in the gas–solid flow, which in turn affects the cluster size and motion.

1.4.5 Wake-Induced Phenomena

Problem Statement: In multiphase suspensions, it is commonly seen that falling drops or rising bubbles align with the stream. This also happens to particles when they are settling in a liquid. What causes the alignment; can it be understood through a simple mechanistic model?

Analysis: In a multiphase flow, due to the relative velocity between the fluid and particles, there is a wake region of each individually suspended particle. The random fluctuation in the particle motions causes a situation where some particles fall into the wake regions of other particles. When this occurs, the drag force on the trailing particle is suddenly reduced due to the low pressure in the wake, leading to an accelerated approach ("drafting") and eventual collision ("kissing") of the pair. The vertical in-line configuration of the pair may become unstable and encourage tumbling, causing the prior trailing particle then to take the lead. The new trailing particle, originally the leading one, can be attracted to the wake of the new leading particle and the cycle repeats. This drafting-kissing-tumbling phenomenon of settling particles (Fortes *et al.*, 1987; Feng *et al.*, 1994) is illustrated in Figure 1.4-4.

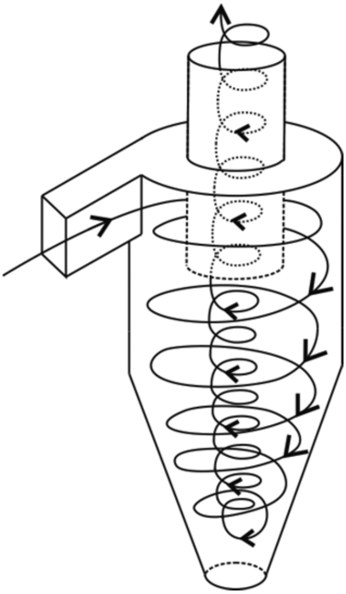


Figure 1.4-5 Trajectories of fluid tracers in a tangential inlet cyclone.

Rising bubbles and falling drops also undergo drafting, aligning, colliding, and even rotating about each other (Fan and Tsuchiya, 1990; Joseph and Renardy, 2013). In most cases, they tend to stay in line with an equilibrium distance at which the wake-induced attractive force and potential repulsive force balance (Yuan and Prosperetti, 1994).

Comments: This case study illustrates the mechanistic effects due to wakes on particle or bubble motion. Note, that with the governing mechanism identified in a given multiphase flow (*i.e*., the wake phenomena in the particle or bubble flow of this case) a simple model that includes this governing mechanism can reasonably be used to characterize this flow phenomenon.

1.4.6 Particle Trajectories in a Cyclone Separator

Problem Statement: In a numerical simulation of gas–solid flow in a cyclone, the flow field is calculated using a commercial CFD code. In order to study the collection efficiency, trajectories of fluid tracers are plotted, as schematically exemplified in Figure 1.4-5. However, it appears that all tracer trajectories are leading to the cyclone exit, which means no collection of particles. What is wrong with the modeling or simulation?

Analysis: The velocity and pressure fields of fluid phase (air in this case) are solved using the Eulerian equations of mass and momentum conservations. Since the flow is turbulent, the transport properties or Reynolds stresses need to be solved by using a turbulence model. For simplicity, the standard k–ε model was employed here;

although, for better predictions, a more advanced turbulence model that accounts for the effects of buoyancy, wall, and multiphase turbulence modulation could be substituted. The trajectories of fluid tracers hence are obtained from integrating the associated fluid velocities, as demonstrated by path lines in Figure 1.4-5. It is important to understand that an ideal fluid tracer (such as the one in CFD simulation) is a conceptual fluid element having the fluid density but no volume. That is, the fluid tracer cannot represent a solid particle that has not only a different material density but also a finite volume. Hence, the dynamic response and transport characteristics of a solid particle are different from those of a fluid tracer. To obtain the collection efficiency of solids in a cyclone, trajectories of solids have to be solved separately from (and maybe coupled with) the carrying fluid flow, which are typically described by Lagrangian trajectory models of particles.

Comments: This case study illustrates a common misunderstanding between flow patterns (marked by trajectories of fluid tracers) and the trajectories of actual particles in multiphase flow applications. While the concept of a fluid tracer is simple, the actual use of it in real applications can be confusing since the actual fluid tracers for flow visualization, used primarily for illustrative purposes only, are real particles (such as droplets, bubbles, and solid spheres) whose dynamic transport would be different from that of fluid phase. The key in selecting those “tracer particles” in a multiphase flow application is ensuring that the dynamic response is nearly identical to that of fluid phase, yet far away from those of concerned particle phases in the application.

1.5 Summary

This chapter provides an overview of the concepts and exemplified applications of multiphase flows. It illustrates the distinctly different transport patterns or phenomena of individual phases in a multiphase flow, which either have naturally caused or intentionally designed consequences.

The chapter conveys the basic definitions of a multiphase flow, the phase interactions, and the associated modeling approaches, which include:

- the difference between a multiphase flow and a multicomponent single-phase flow, and hence identification of each phase and component involved;
- the difference between a dilute-phase multiphase flow and a dense-phase multiphase flow, and hence determination of the inclusion or exclusion of interparticle interactions in the multiphase flow of interest;
- the difference between a continuum phase and a discrete phase in describing the flow regimes;
- the difference in Eulerian–Lagrangian modeling and Eulerian–Eulerian modeling, and the intents of each approach.

In the case studies, the unique phenomena of multiphase flows are discussed that involve:

- hydrodynamic forces governing the motion of a bubble in liquid;
- pressure drop reduction in a particulate-laden pipe flow;
- clusters and their transport characteristics in a particulate-fluid flow;
- wake-induced particle motion and collision;
- motions of ideal fluid tracers and real particles in a cyclone flow simulation.

Nomenclature

A	Cross-section area
C_A	Shape factor of carried mass
C_D	Drag coefficient
D	Pipe diameter
d	Particle diameter
F_D	Drag force
g	Gravitational acceleration
n	Richard-Zaki index
P	Pressure
r	Radial coordinate in a cylindrical coordinate system
t	Time
U	Velocity
V	Volume
z	Axial coordinate in a cylindrical coordinate system

Greek symbols

α	Volume fraction
μ	Dynamic viscosity
ρ	Density
τ	Shear stress

Subscripts

0	Particle-free
b	Bubble
l	Liquid
s	Solid
T	Turbulence
w	Wall

Problems

P1.1 What is the major difference between a multiphase flow and a multicomponent flow? Give an example for each flow.

P1.2 List the major advantages and disadvantages between a Lagrangian–Eulerian model and an Eulerian–Eulerian model for modeling a bubble column (gas–liquid) bioreactor.

P1.3 Consider a mono-droplet generator that relies on an atomized nozzle spray of liquid with a cross-flow air blowing. How many dynamic phases should be considered in this application?

P1.4 Identify if the following flow phenomena or applications belong to the category of single-phase flows or multiphase flows. For a multicomponent phase, identify the multiple components:

(a) cold nitrogen jet into a hot steam stream;
(b) mist flow generated by ultrasonic humidifier;
(c) wind and cloud movements;
(d) liquid fuel spray in engine; and
(e) underground water flow through porous layer of rocks.

P1.5 Identify if the following flow systems or applications belong to the category of single-phase flows or multiphase flows. For a multicomponent phase, identify the multiple components:

(a) crude oil-natural gas flow through porous layer of rocks;
(b) liquid coolant flow with boiling in porous layer of solids surround a nuclear reactor;
(c) mono-sized solid particle movement in a vacuum container on a vibrator; and
(d) rotating hybridizer of granular particles (with a loop structure of centrifugal fan and pipe bend).

P1.6 Identify if the following flow systems or applications belong to the category of single-phase flows or multiphase flows. For a multicomponent phase, identify the multiple components:

(a) ball miller (in vacuum or inert gas container);
(b) dry coating of fine particle on coarse particle in a vibrating vacuum container;
(c) segregation of solids in dry powder mixture;
(d) pulverized coal combustion.

P1.7 Scaling two-phase flows to Mars and Moon gravity conditions: The interest in the liquid-vapor two-phase flows for space applications requires the understating of such flows under different gravity conditions. An experiment was conducted to investigate the relation between pressure drop in a pipe and the gravity. It is found that in the annular flow regime, their relationship can be expressed by $Eu = 12.7\mathrm{Fr}^{0.41}$ (Hurlbert *et al.*, 2004). The gravity is 1.622 m/s^2 on moon, and 3.71 m/s^2 on Mars. If a pressure drop of 1,000 Pa is measured during an experiment on Earth, what will be the pressure drop in the same pipe if the same experiment is carried out on Mars and on the Moon with the same fluid and velocities of the two phases?

P1.8 Porous filters are often used for filtration and purification of fluid with impurities such as dust particles, oil drops, or bacteria. While the filter size often ranges from centimeters to meters, the impurities and the pores are of only micrometer or nanometer size. Describe the multiphase flow phenomena on different scales and interaction between scales.

P1.9 Pneumatic conveying is a common method to transport dispersed dry powders via gas pipe flows. Consider a pneumatic conveying of fine powder dispersed in an air flow through a pipe of 50 mm in diameter. The transport is undertaken at the atmosphere pressure and room temperature, with an average air velocity of 30 m/s and a mass flow rate of 0.1 kg/s of fine powders. The average size of powder is 100 μm, with a density of 1,500 kg/m^3. Is the pipe flow turbulent or laminar? Do you expect any pressure drop reduction in this pneumatic transport?

P1.10 Droplets injected from a spray nozzle are typically polydispersed (*i.e.*, of different sizes). The sprayed droplets from a lawn sprinker (such as the one in Figure 1.1-5) consist of three different sizes: mist (*e.g.*, $d_d < 100\mu$ m), fine (*e.g.*, 100μ m$d_d < 1$ mm), and coarse (*e.g.*, 1 mm $< d_d < 10$ mm). If the injection velocity and angle are the same for all droplets, do the different-sized groups of droplets have the same watering coverage area if there is no wind? If there is a strong cross wind, how does the wind alter the watering coverage area? Can mist cover further than the coarse droplets do under a strong crosswind?

P1.11 In the hydraulic fracking process of crude oil and natural gas production, a well is drilled vertically beyond a mile under surface to extract the fluid that is under enormously high pressure. The extracted fluid is a mixture of natural gas, oil, sand, salts, and water that was originally in a supercritical state (*i.e.*, at pressures higher than the critical pressure of the mixture). As the fluid is extracted to the surface, the pressure is drastically reduced down to the ambient pressure (such as the atmospheric pressure). How many different dynamic phases are there in the pipe flow during the fluid extraction from the shale (where the fluid is originated) to the surface?

P1.12 In the vapor-compression air-conditioning system, the refrigerant recirculates in a closed piping loop that is connected through an evaporator, a compressor, a condenser, and a throttling valve. Analyze the dynamic phase (*i.e.*, single-phase or two-phase) of refrigerant flow when it goes though each of these components.

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