PARTICLE TECHNOLOGY

1. Introduction

Particulate systems are involved in numerous industrial processes and are present in various natural phenomena. Particle technology is a term that refers to the field of the science and technology associated with the characterization, formation, processing, and utilization of particles. It is concerned with the systems in which one or more of the components are in the form of particles. The terms particles, powder, and particulate solids are often used interchangeably, and thus particle technology is often also referred to as powder technology. Recently, the scope of particle technology has been extended to cover systems containing nanoparticles, aerosols, liquid droplets, emulsions, and bubbles.

The range of particulate systems of industrial importance is vast, as is the range of processes involving particulate systems. Most of the industrial practices that engage in energy, chemicals, petroleum, agricultural, food, minerals, pharmaceuticals, environmental, and advanced materials, utilize particles, or powders in the course of operation. Hence, understanding particle science and technology is essential to ensuring successful particle synthesis and handling, particulate process design, and optimization in operation. Catalyst particles alone account for >500,000 metric tons of annual sale globally. Major uses for these catalysts are in fluid catalytic cracking (FCC) ($\sim$78%) and hydrotreating/hydrorefining ($\sim$20%) (1). Table 1 lists examples of various particulate systems used in different industrial processes.

With the advances in particle technology, the physical and chemical characteristics of particles are modified and new generation devices are developed to meet the needs of innovative particulate and multiphase systems including micorfluidics. The development of particle technology contributes not only to the economic well being of nations, but also to a safe and healthy living environment. For each particulate system, the following aspects must be considered in its design and development: particle characterization, transport principles, formation, and processing mechanisms. Modeling and computation are also used to analyze and optimize the process operation and scale up, while measurement techniques are developed to provide insight into the flow and transport properties of particulate units, and physical and chemical characteristics of the particles.

Particle technology is an interdisciplinary field. Due to the complexity of particulate systems, particle technology is often treated more as art than science. Hence, efforts in synthesizing, measuring, modeling, and developing particle and particulate systems are being pursued actively in both academia and industry. In what follows, the fundamental principles governing the key aspects of particle science and technology are described.

2. Particle Characterization

2.1. Particle Morphology. Particle morphology refers to a geometric description of the size, shape, and structure of a particle. It also includes

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interrelationships between individual particles and particle clusters or agglomerates (2).

Size Definition.   The size of a spherical particle is defined either by its diameter or its radius. The size of a nonspherical particle usually refer to as an equivalent diameter, which is based on either the geometric equivalence (eg, volume or surface area) or an equivalence in dynamic characteristics (eg, terminal velocity). Thus, for a given nonspherical particle, >1 equiv diameter can be defined. The selection of a desired definition is often based on the specific process application intended. Typical equivalent sizes and corresponding sizing methods are listed in Table 2.

Sizing Methods.   A broad spectrum of physical principles are employed in various particle sizing methods, including mechanical, optical, electronic, dynamic, physical, and chemical principles (3). The typical particle sizing methods are listed in Table 3.

Sieving is the most common mechanical sizing method. Sieving is based only on the size of the particles and is independent of other particle properties (eg, density, optical properties, and surface roughness). The common sieves are made of woven wire cloth and have square apertures. Two different sets of standard series, the Tyler Standard and the U.S. Series ASTM Standard, are popularly adopted. The mesh number of a sieve is normally defined as the number of apertures per unit area (in.^{2}).

Common types of microscopy techniques include optical microscopy, transmission electron microscopy (TEM), and scanning electron microscopy (SEM). The TEM generates an image of a particle sample on a photographic plate by means of an electron beam, through the transmissibility of the electron beam on the sample. The SEM uses a fine beam of electrons of medium energy to scan across the sample in a series of parallel tracks. These scanning electrons produce secondary electron emission, back scattered electrons, light, and X-rays that can be detected. Both the TEM and SEM are extensively used in the determination of the pore structure and surface shape and area of the particle. The sample preparation procedure of the SEM technique is considerably simpler and the SEM measurement gives more three-dimensional (3D) information than the TEM technique, while the maximum magnification of the TEM is greater than that of the SEM.

Optical-based particle sizing techniques are also developed using light scattering and diffraction characteristics. The most common techniques include the laser phase Doppler shift method and the Fraunhofer diffraction method. When a spherical particle enters the crossing volume of two laser beams, a Doppler effect occurs not only in the frequency shift, but also in the phase shift of the scattered light. The frequency shift yields the velocity of the sphere, whereas the phase shift gives the particle size. The Fraunhofer diffraction method is based on a simplified Larenze-Mie theory and it is applied for particles much larger than the wavelength of light. To obtain the Fraunhofer diffraction, it is also required that the area of the particle must be smaller than the product of the wavelength and the distance from the particle to the observation plane. Hence, the Fraunhofer diffraction is known as far-field diffraction. Both the phase Doppler and the Fraunhofer diffraction methods require the particles to be spherical.

Dynamic methods employ sedimentation and inertia impaction for particle size measurements. The sedimentation techniques utilize the dependence of the terminal velocities of particles on their size either in a gravitational field or in a centrifugal field. The lower bound of the particle sizing by sedimentation is limited by the effects of convection, diffusion, and Brownian motion, as well as the long settling time involved. The sedimentation methods are normally used to measure the size of particles in a liquid medium because of the relatively high viscosity effects in liquids compared to gases. The solvation of particles in a liquid usually has little effect on the particle sizing results. Another innovative design for particle size measurement is developed using the inertial technique. A cascade impactor consists of a series of collecting plates of the particle-laden gas flow, which is gradually increased in the form of a succession of jets. Thus, the particles are deflected by inertia in jet flows, classified and collected on the series collecting plates.

The Coulter counter is an instrument for size measurements using an electrical sensing technique. In the Coulter counter, particles are first suspended in an electrolyte and then passed through a small orifice. The orifice has immersed electrodes. When a particle passes through the orifice, it displaces electrolyte within the orifice, which results in a change in impedance leading to a voltage pulse with amplitude proportional to the volume of the particle. By regulating, sizing, and number counting of the pulses, the particle size and size distributions are obtained.

Size Distributions.   The above mentioned particle size measurement techniques can be applied to either individual particles or a group of particles. When a group of particles is used, it is important to select the measuring sample that represents the bulk properties of the particulate system of interest because insufficient sampling size and method can cause inaccurate results. From the particle sizes obtained from the measurements, a mean diameter that represents the average size of the group of particles can be estimated as listed in Table 2. In some cases, the particle size distribution itself provides important information regarding the particulate systems.

A particle size density function can be defined in terms of either the number of particles or the mass of particles within a given size range. A number density function, $f_N(b)$, is defined so that $f_N(b)db$ represents the particle number fraction in a size range from b to $b + db$. Alternatively, a mass density function, $f_M(b)$, represents the particle mass fraction within the size range of b to $b + db$ of the sample particles. The number density function is interconvertible to the mass density function by equation 1

$$f_M(b) = A_M b^3 f_N(b) \tag{1}$$

where A_M is determined from the normalization condition of

$$\int_0^\infty f_M db = 1 \tag{2}$$

There are three simple distributions commonly used in particle classifications, namely, Gaussian distribution, log-normal distribution, and Rosin–Rammler

distribution. The Gaussian distribution is also known as the normal distribution. For a given particle size range bounded by d_1 and d_2, the Gaussian density function is given by

$$f_N(d) = \frac{1}{\sigma_d} \sqrt{\frac{2}{\pi}} \left[\text{erf} \left(\frac{d_2 - d_0}{\sqrt{2}\,\sigma_d} \right) + \text{erf} \left(\frac{d_0 - d_1}{\sqrt{2}\,\sigma_d} \right) \right]^{-1} \exp \left(-\frac{(d - d_0)^2}{2\,\sigma_d^2} \right)$$

(3)

where d_0 is the arithmetic mean diameter and σ_d is the standard deviation. Typical particles show the Gaussian distribution. On the other hand, most systems of fine particles have the log-normal type of particle size distribution. Equation 2 expresses the density function for the log-normal distribution.

$$f_N(d) = \frac{1}{\sqrt{2\pi}\,\sigma_{dl}\,d} \exp \left[-\frac{1}{2} \left(\frac{\ln d - \ln d_{0l}}{\sigma_{dl}} \right)^2 \right]$$

(4)

Here d_{0l} is the median diameter and σ_{dl} is the natural log of the ratio of the diameter for which the cumulative-distribution curve has the value of 0.841 to the median diameter. Note that $\ln d_{0l}$ and σ_{dl} are not equivalent to the arithmetic mean and the standard deviation of $\ln d$, respectively, for the log-normal distribution. For many irregular particles, eg, broken coal and moon dust, the mass distribution is likely to follow the Rosin−Rammler distribution. A Rosin−Rammler cumulative distribution function F is expressed as

$$F = \int_0^d f_M(b)\,db = 1 - \exp(-\beta d^\alpha)$$

(5)

where α and β are constant. The corresponding Rosin−Rammler density function is thus obtained by equation 6.

$$f_M(d) = \alpha\beta d^{\alpha-1} \exp(-\beta d^\alpha)$$

(6)

Shape.   As illustrated in the differences in particle size distributions, the particle shape can be a significant factor for the properties of the particulate systems. Compared to smooth spherical particles, the surface area per unit volume is greater for the irregular shaped particles. The particle shape also affects the flowability of powders, their packing, and the covering power of pigments. Qualitative definitions for particle shapes are given in Table 4.

The shape of particles is commonly expressed in terms of shape factors and shape coefficients. One most common shape factor is sphericity, which is defined as the ratio of surface area of a sphere having the same volume of the nonspherical particle to the actual surface area of this particle.

Porosity.   In addition to the increase in the outer-surface area due to irregular shapes of the particles, the overall surface area available for physical or chemical interactions can be significantly higher if the material is porous (4). For a given porous particle, the effective surface area is defined on the basis of

the specific transport phenomenon of interest in a process system. For example, thermal radiation may be affected predominantly by the external surface area of the particle and the exposed surface area due to superficial cracks and fissures. On the other hand, for most chemical reactions and adsorption processes, the internal surface area provided by the interior pores of the particle may determine the overall rate process (4). A convenient classification of pores according to their width divides them into three categories: micropores, <20 Å; mesopores, between 20 and 500 Å; and macropores, >500 Å. For agglomerate composed of nonporous fine particles (eg, nanoparticles), a large specific surface results from the accumulation of the external surface of those fine particles rather than internal pore surface area (5).

The most common method used for the determination of surface area and pore size distribution of particles is physical gas adsorption. Nitrogen, krypton, and argon are some of the typically used adsorptives. The amount of gas adsorbed is generally determined by a volumetric technique. A gravimetric technique may be used if changes in the mass of the adsorbent itself need to be measured at the same time. The nature of the adsorption process and the shape of the equilibrium adsorption isotherm depend on the nature of the solid and its internal structure. The Brunauer–Emmett–Teller (BET) method is generally used for the analysis of the surface area based on monolayer coverage, and the Kelvin equation is used for calculation of pore size distribution.

2.2. Particle Properties

Density. Although a material density is commonly used to characterize products, there are other definitions of the density employed specifically in particle technology, namely, bulk, particle, and skeletal densities (3). It is important to understand the differences between these densities, because their relationships provide important information (eg, voidage in packed bed of particles and particle porosity) needed for designing particulate flow systems.

The bulk density of the particles is the overall density of the particulate system including the interparticle volumes occupied by fluid medium (eg, air or water). It is defined as the overall mass of the material per unit volume occupied. The bulk density depends on the method of packing and a system of packed particles can become denser with time and settling process. The limiting value is known as the tapped or packed bulk density.

Particle density is the density of a particle including the pores or voids within the individual particles. It is defined as the weight of the particle divided by the volume occupied by the entire particle. Particle density is sometimes referred to as the material's apparent density. Direct measurement of particle density can be made by immersing a known mass of particles in a nonwetting fluid, eg, mercury, which does not penetrate into the pores. The volume of the particle corresponds to the volume change of the fluid.

The skeletal density, also called the true density or material density, is defined as the density of a single particle excluding the pores. Measurements of the skeletal density can be made by liquid or gas pycnometers. Among three densities, the bulk density is smallest. For nonporous materials, the skeletal and particle densities are equivalent, whereas for porous particles, the skeletal density is greater than the particle density. Note that these relationships are

generally true except for rare systems of the surrounding medium that is denser than the particles.

Flowability.   Flowability is another important property for designing and operating particulate systems, eg, pneumatic conveying and multiphase reactors. The initiation of powder flow is due to the incipient failure where the forces acting on the solid produce stresses in excess of the strength of the solid. The rupture of powders depends on the mechanical properties of bulk solids including the angle of internal friction, the kinematic angle of internal friction, the kinematic angle of wall friction, bulk density, unconfined yield strength, major principal stress, and cohesion.

Flowability of dry powders can also be described in light of the fluidization properties and the flow regimes. The classification, known as Geldart's classification, is shown in Fig. 1, where particles are classified in terms of the density difference between the particles and the fluidizing gas, and the average particle diameter. Group C is comprised of fine particles that are cohesive with strong interparticle contact forces, eg, the van der Waals, capillary, and electrostatic forces. Thus, Group C particles (eg, flour) are difficult to fluidize and gas channeling is the most common characteristic when fluidizing these particles. On the other hand, both Groups A and B particles are readily fluidized. Beds with Group A particles (eg, FCC catalyst) can be operated in both the particulate fluidization regime and the bubbling fluidization regime where bubble-like voids are present. For Group B particles (eg, sand), there is no particulate fluidization regime, where initial bed expansion occurs without formation of bubbles. Group D is comprised of coarse particles (eg, grains) that are commonly processed by spouting.

There are other important flow properties, eg, the angle of repose, angle of fall, compressibility, and dispersibility that provide additional measures for the flowability of granular materials when discharged out of a transport system, eg, a hopper. In general, flow properties are influenced by the conditions under which they are handled, eg, moisture content, storage time at rest, and consolidating pressure. All of these properties can be determined with simple bench-top equipment, eg, the Jenike translatory shear cell and the rotational split-level shear cell.

Chargeability.   Particles in a flow system can be charged via various modes including triboelectric charging by surface contact, field charging, and charging by thermionic emission. Electrostatic charging of particles is important because as the electrostatic charges are accumulated in a multiphase flow, particles begin to agglomerate and in some cases the charge accumulation results in sparks leading to fires or explosion. Dust explosion in silos and hoppers is an example of this phenomenon. Gas–solid reactors used for polymer production (eg, polyethylene) also experience significant charging effects that cause sheet formation instead of pellets.

A maximum accumulated charge on a surface is limited by the breakdown electric field strength of the surrounding medium. The limiting net surface charge density can be estimated based on Gauss' law. At atmospheric pressure with air as the medium, eg, only <10 atoms per million atoms on the surface are charged. Such a small percentage of surface atoms participating in

the charge transfer indicate the high sensitivity of the surface impurity and treatment on the electrostatic charging and charge transfer.

Triboelectric charging is due to surface contact. When two surfaces of dissimilar materials are brought into contact, charge transfer occurs through the contact surface as a result of the difference in the initial Fermi energy levels of these materials. The contacting solids become electrostatically charged after their separation from the contact, with opposite charge polarities. Most solid materials can be arranged into a triboelectric series based on charge polarity in a simple contact and separation process.

Particles can also be electrified in an electric field via three distinct charging mechanisms: field, diffusion, and corona charging. Field charging becomes predominant for large particles where the diffusion charging mechanism can be ignored. For submicron particles, the diffusion charging must be accounted for and the contribution of an external electric field becomes insignificant. When the electric field strength exceeds a certain limit, ionization of the surrounding gaseous medium occurs. By the bombardments of the ions and electrons, the solids are charged. Such a charging process is known as corona charging.

When solid particles are exposed to a high temperature environment, the electrons inside the solid can acquire the energy from the high temperature field and be freed by overcoming the energy barrier or the work function. By losing electrons in such a thermionic emission process, the particles are thermally electrified.

Adsorption. Adsorption is the accumulation of gas on a solid surface. The outermost layer of the solid molecules on the surface is bound on only one side to the inner layer of molecules by atomic and molecular forces. To compensate for this imbalance of the binding force, an attraction force from the solid surface captures the surrounding gas, vapor, or liquid. This attraction can be either physical or chemical, depending on the temperature and the interacting forces between the solid and surrounding fluid.

Physical adsorption, or van der Waals adsorption, results from a relatively weak interaction between the solid and the gas. The forces responsible for adsorption are "dispersion" forces and electrostatic forces. Physical adsorption is reversible; hence all the gas adsorbed by physical adsorption can be desorbed by evacuation at the same temperature. Chemical adsorption is a result of a more energetic interaction between the solid and the gas than that of physical adsorption. Reversal of chemical adsorption using a vacuum requires an elevated temperature and even that may not be sufficient.

Physical adsorption can be estimated according to the adsorption isotherms in which the amount adsorbed is expressed as a function of the partial pressure of the adsorbate at a constant temperature. The most important empirical isotherm is the Freundlich isotherm. The Langmuir isotherm describes the localized adsorption with monolayer coverage on homogenous materials. The BET Isotherm is a modified Langmuir approach of balancing the rates of adsorption and desorption for the various molecular layers. In particulate systems, the BET isotherm is used to determine surface area and porosity of particles or powder based on the gas adsorption technique.

3. Transport Principles of Particulate Flows

The flow characteristics of solid particles in a multiphase flow vary significantly with the geometric and material properties of the particle. In the following sections, the basic equations and phenomena of particulate flows, whose principles are used for particle formation and processing, are presented.

3.1. Contact and Collision Mechanics of Solids. The onset of powder motion is due to stress failure in powders. The local distributions of static stresses of powders can be obtained by solving the equation of equilibrium. From stress analysis and suitable failure criteria, the rupture locations in granular materials can be identified (6).

The most common failure criterion for granular materials is the Mohr–Coulomb failure criterion introduced by Mohr in 1910. The material most likely fails along a plane when a critical combination of normal and shear stresses exists on the failure plane. The Mohr–Coulomb failure criterion can be recognized as an upper bound for the stress combination on any plane in the material. Since the Mohr–Coulomb failure envelope characterizes the state of stresses under which the material starts to slide, it is usually referred to as the yield locus. A rigid-plastic powder, which has a linear yield locus, is called a Coulomb powder. Most powders have linear yield loci, although, in some cases, nonlinearity appears at low compressive stresses.

In particulate flows, collision occurs between the particles or between the particle and the wall. A collision without permanent deformation or heat generation is called an elastic collision. Otherwise, the collision is inelastic and energy loss occurs mainly in the form of permanent deformation, eg, particle breakage and frictional heat loss. Basic modes of two-body collision include the normal collision, the oblique collision with or without tangential sliding, or the collision with a compressional twist (2).

The simplest theory of impact is the stereomechanics of rigid bodies, which yields a quick estimation of the velocity after collision and the corresponding kinetic energy loss. The stereomechanics, however, does not yield some key impact information, eg, transient stresses, collisional forces, impact duration, or collisional deformation of the colliding objects. The normal contact of elastic bodies is modeled by the Hertzian theory; the oblique contact is delineated by the Mindlin's theory; and the contact with a compressional twist is described by the Lubkin's theory. In order to link the contact theories to collisional mechanics, it is assumed that the process of a dynamic impact of two solids can be regarded as quasistatic, which is valid when the impact velocity is small compared to the speed of the elastic wave. For inelastic collisions of particles, additional modeling of the inelastic mechanisms, eg, plastic deformation or surface friction, is needed.

3.2. Charge Transfer and Charging Mechanisms. Major modes of particle electrification include surface contact, ion collection, thermionic emission, and frictional charging (2). Dielectric particles can also be polarized in an external electric field, in which opposite charges occur at both ends of the particle surface while the net charge on the particle remains neutral.

Electrification by surface contact is known as triboelectric charging. The word tribo, meaning "to rub", is from Greek. The triboelectric charging does not require any rubbing processes other than surface contact. Rubbing or collision can enhance the charge transfer due to an increased contact area. The charging mechanism is due to the requirement of charge equilibrium between two objects in contact. When two dissimilar materials are brought into contact, charge transfer occurs through the contact surface as a result of the difference in the initial Fermi energy levels. After their separation from the contact, one particle is positively charged due to the loss of electrons while the other is negatively charged because of the gain of electrons. Most solid materials can be arranged into a triboelectric series based on charge polarity in a simple contact and separation process.

Particle charging by ion collection in an electric field is achieved via three distinct charging mechanisms: field charging, diffusion charging, and corona charging. Field charging becomes predominant for particles $>1\,\mu m$, where random motion of ions is insignificant and, thus, the diffusion charging mechanism can be ignored. For particles $<0.2\,\mu m$, diffusion charging must be accounted for and the contribution of an external electric field becomes insignificant. When the electric field strength exceeds a certain limit, ionization of the surrounding gaseous medium occurs. The solids are charged by the bombardments of the ions and electrons. Such a charging process is generally known as corona charging.

Thermal electrification becomes important when particles are exposed to a high temperature environment. The electrons inside the solid can acquire the energy from the high temperature field and be freed by overcoming the energy barrier or the work function. By losing electrons in such a thermionic emission process, the particles are electrified. There exists the maximum thermal electrification of a solid particle due to the equilibrium between the thermionic tendency to free an electron and the attracting Coulomb force to recapture the to-be-freed electron.

3.3. Momentum Transfer.   In multiphase flows, flow patterns of each phase depend not only on the initial conditions and physical boundaries of the system, but also on the mechanisms of momentum transfer or interacting forces between phases (7). The forces controlling the motions of particles may be classified into three groups: (1) forces through the interface between fluid and particles, (2) forces due to the interactions between particles, and (3) forces imposed by external fields.

(A) Fluid-Particle Interactions.   An arbitrary motion of a particle in a fluid flow may be logically decomposed into four types of simple motions: (1) a particle moving with a constant velocity in a uniform flow field, (2) a particle accelerating in a uniform flow field, (3) a particle moving with a constant velocity in a nonuniform flow field, and (4) a particle rotating with a constant angular velocity in a uniform flow field. Such decomposition is valid when the hydrodynamic equation of fluid motion over a particle is linear. All hydrodynamic forces are the result of the unbalanced pressure distributions and viscous shear stresses over the surface of moving particles in fluid flows. Different forces, respectively, representing each type of these simple motions are the drag force, the Boussinesq–Basset historic integral force, the carried mass force, the Saffman force, and the Magnus force.

Drag Force.   The drag force refers to the hydrodynamic force that results from the relative motion of a particle in a uniform fluid flow. The drag force of a particle moving in a Newtonian fluid can be expressed by

$$\mathbf{F}_{\mathrm{D}} = C_{\mathrm{D}} A \frac{\rho}{2} |\mathbf{U} - \mathbf{U}_p| (\mathbf{U} - \mathbf{U}_p) \tag{7}$$

where the drag coefficient C_{D} is typically a function of the particle Reynolds number (Re), particle shape, and orientation. In a particulate multiphase flow, the drag force of a particle may also be affected by its neighboring particles and the local turbulence characteristics.

Historic Force and Carried Mass.   Once a particle is accelerating or decelerating in a fluid, two additional hydrodynamic forces, known as the Boussinesq–Basset historic integral force and the carried mass force, become important. The history integral force accounts for the effect of past acceleration on the flow resistance, whereas the carried mass force contributes to the resistance due to the fact that the acceleration of the particle is also accompanied by acceleration of the surrounding fluid. For a creeping motion of a sphere, equation 8 can be used to obtain the Boussinesq–Basset history integral force.

$$\mathbf{F}_{\mathrm{B}} = \frac{3}{2} d^2 \sqrt{\pi \rho \mu} \int_0^t \frac{1}{\sqrt{t - \tau}} \frac{d}{d\tau} (\mathbf{U} - \mathbf{U}_p) d\tau \tag{8}$$

The carried mass, also termed the added mass or the virtual mass, is the mass of the carried fluid that has the same acceleration as the particle. The volume of the carried mass depends on the particle geometry, and is independent of the acceleration rate and the fluid viscosity. The Basset force can be substantial when the particle is accelerated at a high rate.

Saffman Force and other Gradient-Related Forces.   When a sphere moves in a flow where a velocity, pressure, or temperature gradient exists, additional forces related to these gradients can be as important as the drag force. The Saffman force refers to a lift force caused by the velocity gradient over the particle. For a sphere in a simple shear flow, the Saffman force is given by

$$\mathbf{F}_{\mathrm{S}} = 1.6 \mu |\mathbf{U} - \mathbf{U}_p| d^2 \sqrt{\frac{\rho}{\mu} \left| \frac{\partial (\mathbf{U} - \mathbf{U}_p)}{\partial y} \right|} \tag{9}$$

The Saffman force can be important when a particle is near a wall or in a high shear region.

A resisting force may act on the particle as a result of the existence of a pressure gradient in the fluid, which is in the opposite direction of the pressure gradient. The significance of this force is evident, eg, when a shock wave propagates through a particulate suspension. Radiometric forces include the thermophoresis force due to a temperature gradient or photophoresis force due to nonuniform radiation. The radiometric forces are important only for submicrometer particles. However, under conditions of high temperatures and/or large

temperature gradients, eg, in the process of plasma coating, the thermophoresis effect may also be significant for larger particles.

Magnus Force.   When a particle rotates in a fluid flow, the particle rotation leads to fluid entrainment, resulting in an increase in the velocity on one side of the particle and a decrease in the velocity on the other side. Thus, a lift force is established that moves the particle toward the region of higher velocity. This phenomenon is known as the Magnus effect and the lift force is called the Magnus force. For a sphere rotating with a small angular velocity, Ω, the Magnus force can be expressed by equation 10.

$$\mathbf{F}_{\mathrm{M}} = \frac{\pi}{8} d^3 \rho \Omega \times (\mathbf{U}_p - \mathbf{U}) \tag{10}$$

Note that the rotation of particle at a high angular velocity or with a nonstreamlined shape leads to the flow separation with an asymmetric wake, which complicates the analysis of Magnus force.

(B) Particle–Particle Interactions.   The motion of particles is affected by the short-range interparticle forces, eg, the van der Waals, electrostatic, and collision force (8).

van der Waals Force.   The van der Waals force is an attractive atomic interaction between the instantaneous dipoles formed in the atoms by their orbiting electrons. The van der Waals force exists not only between individual atoms and molecules, but also between solids. The van der Waals force between two spherical solids is given by

$$F_{\mathrm{v}} = \frac{H_{12} d^*}{6 r^2} \tag{11}$$

where H_{12} is the Hamaker's constant; r is the separation distance; and a^* is the relative radius. The van der Waals force becomes extremely important when the separation distance is near or below the absorption wavelength of the solid material. Note that the van der Waals effect is one of the dominant mechanisms in the formation of nanoparticle agglomerates (5). It is also responsible for the cohesive behavior of Geldart Group C dry powders that causes difficulty in fluidizing Group C particles.

Electrostatic Force.   The motion of a charged particle in a particulate flow is affected by the electrostatic force imposed by nearby charged particles. The electrostatic force of a pair of interacting charged particles in an unbound pace without other charged particles or external electric field can be described by Coulomb's law as

$$F_{\mathrm{e}} = \frac{q_1 q_2}{4 \pi \varepsilon r^2} \tag{12}$$

where q_i is the charge carried by particle i; and ε is the permittivity of the surrounding medium.

For a charged particulate suspension flowing in a confined processing system, the electrostatic force is given by equation 13.

$$F_{\mathrm{e}} = q \nabla V \tag{13}$$

where *V* is the electric potential, which can be solved from

$$\nabla \cdot (\varepsilon \nabla V) = -n_{\mathrm{q}} \tag{14}$$

where n_{q} is the charged density.

Collisional Force.   Transport of a particulate flow at high particle loading can be greatly influenced by interparticle collisions. The collisional transfer of momentum in a particle cloud depends not only on the collisional force of a colliding pair, but also on the collision frequency, as well as the modes of collisions, eg, elastic or inelastic scattering. Typical theoretical theories of collisional transfer of dense particle suspension flows include the simple shear flow theory and the granular kinetic modeling theory. In the shear flow theory, the particle shear stress is explicitly related to the particle concentration and rate of strain of particulate flow. In the granular kinetic modeling theory that is based on an analogy between gas molecular dynamics and granular flows of elastic spheres, the collisional stress tensor depends on the granular temperature and rate of strain of granular flow via a set of coupled differential equations.

(C) Field Force.   The motion of particles is also affected by the long-range field forces, also known as the body forces, exerted by various fields outside the flow system, eg, the gravitational, electric, and magnetic fields.

3.4. Heat Transfer.   Multiphase flows involving heat and mass transfer are common in many engineering operations including petroleum refining, nuclear reactor cooling, solid fuel combustion, rocket nozzle jetting, drying, and bulk material handling and transport. In the chemical process industries, reactors for polymerization and hydrogenation commonly require cooling or heating to maintain desired reaction temperature. There are three basic modes of heat transfer, namely, thermal diffusion (heat conduction), convection, and radiation. All three modes may occur simultaneously, or one of them may dominate under certain conditions. In addition, heat associated with phase change and chemical reaction can also contribute to heat transfer in a flow system (2).

Heat Transfer in a Collision.   In a collision between two spheres of different temperatures, heat conduction occurs at the interface. For a normal collision of two elastic spheres at a small Fourier number, the heat transfer can be estimated by

$$Q_{\mathrm{c}} = 2.73(T_2 - T_1)r_{\mathrm{cm}}^2 \sqrt{t_c} \left(\frac{\sqrt{D_1}}{K_1} + \frac{\sqrt{D_2}}{K_2} \right)^{-1} \tag{15}$$

where *D* and *K* are the thermal diffusivity and conductivity of particles, respectively; r_{cm} and t_{c} are the maximum contact radius and contact time of the Hertzian collision. For collisions at high Fourier numbers, more heat transfer occurs.

Convective Heat Transfer.   The heat transfer rate between a fluid flow and suspended particles are expressed by eequation 16 according to Newton's cooling law:

$$q_f = hA(T - T_{\mathrm{p}}) \tag{16}$$

The convective heat transfer coefficient h is calculated from the Nusselt number, which is in general a function of Re and Prandtl number (Pr) in the following form:

$$\text{Nu} = C_1 + C_2\,\text{Re}^m\text{Pr}^n \tag{17}$$

where the coefficients C_1, C_2, m, and n depend mainly on the flow regime and particle concentration.

Thermal Radiation.   An element in a thermally radiative environment absorbs, reflects, refracts, diffracts, and transmits incoming radiative heat fluxes, as well as emits its own radiative heat flux. Most solid materials in gas–solid flows, including particles and pipe walls, can be reasonably approximated as gray bodies so that absorption and emission can be readily calculated from Stefan–Boltzmann's law for total thermal radiation or from Planck's formula for monochromatic radiation.

The thermal radiation with a particle cloud may be conveniently studied by a simple model in which the radiant flux is all the way through a scattering medium of monodispersed spherical particles. Here, the scattering represents the combined effects of reflection, refraction, diffraction, and transmission of the radiation by the particles. The radiation transport equation can be expressed by equation 18.

$$dI(s,\theta,\varphi) = -\sigma_{\text{e}\lambda}I(s,\theta,\varphi) + \sigma_{\text{a}\lambda}I_{\text{b}\lambda}(s) + \frac{\sigma_{\text{s}\lambda}}{4\pi}\int_0^{2\pi}\int_0^{\pi}I(s,\theta',\varphi')S(\theta,\varphi,\theta',\varphi')\sin\theta'd\theta'd\varphi'$$

$$\tag{18}$$

where I represents the local monochromatic radiant intensity; σ's are the monochromatic coefficients for extinction, absorption, and scattering, respectively; S is the scattering phase function; and $I_{\text{b}\lambda}$ is the Planck intensity function.

Latent Heat and Reaction Heat.   Heat transfer also occurs during a phase change. Latent heat results from a physical phase change, whereas reaction heat is generated from a chemical phase change or chemical reaction. In many cases, heat generated or required during chemical processes are significant, and thus, heat transfer is one of the main design parameters for chemical reactors to maintain the desired reaction temperature. Systems, eg, fluidized-bed reactors allow rapid heat transfer, as well as mass transfer and prevent the development of hot spots inside the reactor.

3.5. Mass Transfer.   The transfer of mass from one point to the other may take place by two different modes, namely, diffusion and convection. The basic mechanisms for these modes of mass transfer are similar to those for heat transfer discussed earlier. Specifically, the mechanism for mass convection is analogous to heat convection and that for mass diffusion is analogous to heat conduction. In addition, physical and chemical changes of the multiphase system may also result in mass transfer in a flow.

Diffusion and Convection.   Mass or molar diffusion is characterized by small-scale "random-walk" motion caused primarily by molecular collisions. The flux of diffusion follows the spatial gradients of a specific local driving

force. If the driving force is concentration, the mass diffusion is termed ordinary diffusion. If the driving force is pressure (as in centrifugal separation) or temperature (as in thermophoresis), the mass diffusion is called pressure or thermal diffusion, respectively. The direction of the flux is from the high to the low driving force.

Mass convection may be due to the bulk motion of the carrier gas or may be associated with the drift of the solute through the carrier gas as a result of net forces applied directly to the solute (eg, centrifugation due to centrifugal force). The primary interest in the mass transfer occurring in a multiphase flow concerns the intraparticle diffusive mass transfer and interfacial convective mass transfer between the particles and the fluids. In both cases, Fick's equation or a more general form of the flux equation can be applied.

Physical Phase Change.   A physical phase change refers to the thermodynamic transformation of a substance from one phase to another, without any change in the chemical composition of the substance. A phase transition is generally indicated by abrupt change in one or more physical properties. Important physical phase changes in the particle processes include melting, freezing, boiling–evaporation, condensation, sublimation, solidification, deposition, and sintering.

Chemical Phase Change via Chemical Reaction.   A phase transition is also induced by chemical reactions, eg, isomerization, chemical decomposition, single replacement or substitution, double replacement or coupling substitution, chemical synthesis, and combustion. The thermodynamics of the system determines whether the given reaction will take a place under specific reaction conditions, while the reaction kinetic determines how fast the given reaction will occur. Heterogeneous reactions including catalytic reactions take place in multiple steps (4): (*1*) mass transfer (diffusion) of reactant A from the bulk fluid to the external surface of solid reactant B, (*2*) diffusion of reactant A into the pores of the reactant B (if the reactant B is porous), (*3*) adsorption of reactant A onto the surface of the reactant B, (*4*) surface reaction between reactants A and B producing product C, (*5*) desorption of product C from the surface, (*6*) diffusion of product C from the interior to the surface of reactant B, (*7*) mass transfer of product C from the external surface of reactant B to the bulk fluid. The overall reaction rate is determined by the slowest reaction step, which is also called the "rate-limiting" step. A reaction is surface reaction limited, if the rate of the surface reaction is slow, whereas it is diffusion limited if the external and internal resistance (diffusion) is significantly slower. Reacting particles' physical properties, eg, surface area and pore size distribution, affect the external and internal diffusion, and adsorption and desorption processes, and thus, the porosity of the reacting particles are often manipulated to improve the overall reaction rate of chemical processes. Particles of larger pores have less issues related to diffusion, however, if a majority of pores are >20 nm, the surface area to pore volume ratio is reduced, and the structural strength of the particles may be weakened.

4. Particle Formation

The mechanisms of particle formation dictate the sizes and morphological characteristics of particles, and thereto the transport properties of these particles.

Typical particle formation mechanisms include mechanical methods, eg, particle comminution and granulation; phase-change processes, eg, nucleation, sintering, drying, and dissolution; and chemical reaction, eg, ash or soot generation from fossil fuel combustion (2,3). Particle formation is generally used to produce desired solid products, but may also occur in chemical processing units as a secondary or detrimental consequence (eg, fouling).

4.1. Formation by Mechanical Methods

Particle Size Reduction: Comminution and Attrition.   Comminution is an important step in particle processing that produces particles of a desired size and shape. For chemical processes, particle size reduction via comminution is essential to create larger surface area to promote the fast reactions. Mining industries also use the comminution method to liberate valuable minerals embedded within the ore. The comminution equipments are designed or selected based on feed and product rates, material properties (eg, hardness, abrasiveness, toughness, cohesivity–adhesivity, and fibrous nature) and carrier medium (eg, gas or liquid). They are also classified with respect to stressing mechanism (eg, crushing and high velocity impact) and mode of operation (eg, batch or continuous).

Attrition denotes a breakup process of solid particles by collisions. It is a type of high velocity impact comminution method, but attrition is also a common secondary result of high velocity multiphase flows. Attrition can be further classified into fragmentation and abrasion. If the sizes of broken pieces of a particle in a breakup process are of the same order of magnitude as the initial particle, this process is termed fragmentation. If the broken particles are at least an order of magnitude smaller than the initial particle, the breakup process is called abrasion. Thus, in general, fragmentation deals with bodily damage, whereas abrasion is associated with the blunting of corners and edges on the surface of a solid object or mother particle.

Particle attrition can be caused by the relative motion of mechanical parts, eg, a blade in the flow of bulk particles and by the impact of particles with a solid wall or with other particles. To enhance the particle breakup, means of increasing the collision momentum are always helpful, eg, jet-assisted jet milling and gravity-assisted ball milling.

Particle Size Enlargement: Granulation and Agglomeration.   Particle size enlargement is the process by which small particles form a larger mass while keeping the identity of the original particles. Size enlargement techniques include agglomeration, granulation, compaction (eg, tabletting), extrusion, and prilling, and they are widely used in the pharmaceutical, agricultural, mining, ceramic, and food industries.

Particles can be granulated into a solid core with multilayer coatings or agglomerates. Interparticle forces, eg, the van der Waals forces, electrostatic forces, or surface tension generally play important roles in the particle agglomeration processes, as well as forces due to liquid and solid bridges. The particle granulation or agglomerates can be enhanced by adhering smaller particles together via various agitation methods.

Powder Coating.   Another special case of particle size enlargement is powder coating. Powder coating, also known as dry coating, applies a layer of dry powders onto a solid surface. The coating powders are typically applied to the surface by an electrostatic force; by a mechanical force from compression;

by a hydrodynamic force, eg, the inertial force from jet impaction; or by other field forces, eg, the centrifugal force. Similar to the dry granulation, once the coating powders are in close contact with the solid surface, the short-range inter-particle forces, eg, van der Waals force and electrostatic force, provide a strong binding power. In some cases, the coated particles are heat-treated to improve the bond strength via phase change or further bonded to the surface via chemical reactions with the host material.

4.2. Formation by Phase Change

Nucleation and Crystallization.   Nucleation involves the conversion of vapor- or liquid-phase materials to a particle formation, in which a vapor or liquid solution in a saturated state is changed into an unstable supersaturated state by a change in temperature or pressure. Nucleation can be either homogeneous or heterogeneous. The particle from homogeneous nucleation is of one compound and the formation occurs in the entire vapor or liquid phase. The heterogeneous nucleation, eg, vapor deposition, results in the addition of solid materials onto the surface of a host particle. Particles by heterogeneous nucleation are typically of more than one compound. The subsequent precipitation of crystals onto the nucleated particle is called crystallization. Since the nucleation process is often slower than the following crystallization process, small seed materials are frequently added to the system to achieve a faster nucleation step. The formation of white sugar crystals inside a honey jar is an example of nucleation and crystallization. The size and shape of the crystals depend on the operating conditions.

Devolatilization.   Devolatilization refers to a process during which the volatiles resided in solid particles are released by the external energetic excitation, eg, heating. An example of the devolatilization process is pyrolysis of coal. As coal is heated at high temperature ($> 400°C$) in the absence of oxygen, organic materials in coal are rapidly decomposed giving hydrogen-rich volatiles (gas product) and leaving only carbon-rich char as the residue (solid product). During devolatilization, the phase change leads to the significant volumetric change in particles. This in turn results in particle attrition that is evidenced by reduced particle sizes and changed morphological structure.

Droplet Evaporation and Film Coating.   Powders are constantly made from spray drying from slurry in which fine powders are well suspended, dispersed, and/or mixed. Particles formed by drying can be either individual solid particles or agglomerates of particles. Typical methods of drying include drying in hot gases, by hot surface contact, by dielectric heating or thermal radiation, freeze and supercritical drying. The droplet evaporation method can be performed using various mechanisms including liquid pressure spray nozzle, gas-atomizing spray nozzle, gas bubbling through liquid or boiling liquid, and condensation process with fogging. Examples of particles or powders made from droplet evaporation range from instant drink mixes and dehydrated milk to industrial sorbents.

Droplet evaporation can also be utilized in film coating processes, where the slurry or solution is sprayed over a host particle or a solid surface (eg, spray painting for automobiles and plastic furniture). Volatile solvents can also be used to accelerate the drying process. Similar to powder-coating process, the size of droplets generally affects the quality and thickness of the coating layer.

Moreover, the coated layer, eg, a polymeric film may be further cured under heat to form a stronger coating.

Sintering. Particle agglomerates or porous materials can be made by sintering the fine particles in contact beyond the softening temperature of the material (below its melting point). Powders are frequently palletized or molded before sintering to close-pack the particles. Powder sintering can also be applied for dissimilar solid materials. During the sintering process, the pore sizes and morphological structure of the material may be changed, as well as its mechanical strength (eg, the densification of the electrolyte via high temperature cosintering ($>1300°C$) for the solid oxide fuel cell (SOFC) application). Typical materials of sintering include ceriamic, metals, and polymers.

4.3. Formation by Chemical Reaction. Particles with a wide range of chemical compositions are produced via various chemical mechanisms involving reactions, eg, isomerization, chemical vapor decomposition, single replacement or substitution, double replacement or coupling substitution, chemical synthesis, and combustion.
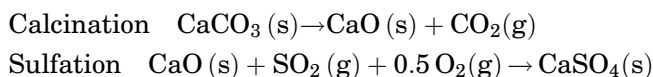
Particle Formation in Liquids. A typical particle formation mechanism from the liquid phase involves chemical reactions and colloidal solution with chemical additives (eg, surfactants), which are used to synthesize particles with desired porosity and sizes (9). Calcium-based sorbents used in the earlier sulfur capture example are synthesized by dissolving lime particles and reprecipitating as fine $CaCO_3$ particles (PCC) in the presence of small quantities of anionic surfactants or surface modifiers. During ionic reaction, a colloid of $CaCO_3$ crystals is formed. A colloid or colloidal dispersion refers to a system containing one or more components whose diameter is between 1 and 1000 nm (9). The anionic surfactant reduces the zeta potential in the $CaCO_3$ colloid system as anions produced from dissociation of the surfactant are adsorbed on the particle surface. Thus, electrostatic repulsion is minimized. Nuclei form aggregates at an early stage during crystallization process. Under these optimized conditions, calcium-sorbents with highly open pore structures having large pore volumes and surface areas are formed. The chemical additives can also influence the particle-size distribution and pore-size distribution of the precipitated particles.

Other examples of industrial and consumer products manufactured using the dispersion of colloids include paint, cosmetics, gels, and emulsions (10). Recently, its application has expanded to innovative materials including color-shifting inks, solar cells, and light emitting displays. Water has been the most widely used solvent for particle formation in the liquid phase via chemical reaction−precipitation−deposition, but environmentally friendly solvents, eg, supercritical CO_2, have also gained significant interests for ease of product separation and minimized posttreatment of solvents.

Particle Formation in Gases. Particles formed in gases can be found both in Nature and industrial processes. For example, airborne submicron-size particles, as well as liquid droplets, are referred to as aerosol. Due to their small size, aerosol resides in the atmosphere for a long period of time and affects the quality of air (11). Aerosol formed in Nature generally originates from volcanoes, dust storms, forest fires, and sea spray, whereas anthropogenic aerosol emission is mostly caused by fossil fuel combustion (eg, soot particles). During the combustion process, coal is injected into a hot furnace−boiler and its volatile and organic

components are quickly vaporized and oxidized in the gas stream. Coal particles become smaller and are eventually reduced to ash or soot (the incombustible component). This particle formation mechanism is termed combustion-particle burnout. Recently, atmospheric aerosol has been suggested as an instigator of global climate change, and many researchers are investigating the characteristics and reactivity of aerosols and their effects on environment.

During chemical processes, particles can be formed as a result of gas–solid reactions. For example, gaseous sulfur dioxide (SO_2) produced from the coal combustion process can be captured by a gas–solid reaction using calcium-based sorbent (eg, PCC). The reactions taking place during the sulfur capture process in a furnace sorbent injection (FSI) mode are

$$\text{Calcination} \quad CaCO_3 \,(s) \rightarrow CaO \,(s) + CO_2(g)$$
$$\text{Sulfation} \quad CaO \,(s) + SO_2 \,(g) + 0.5\,O_2(g) \rightarrow CaSO_4(s)$$

As shown here, industrial processes often simultaneously undergo multiple particle formation mechanisms involving one or more phases (gas, liquid, and solid) to generate a wide range of particles either as desired products or by-products.

Chemical-Vapor Deposition.   Another chemical method of particle formation is chemical-vapor deposition (CVD), which is widely used in microfabrication processes (eg, the semiconductor industry during device fabrication). In this method, the desired thin film is produced by reacting or decomposing volatile precursors onto the surface of the flat substrate or particles. The thin film can be generated in various forms including monocrystalline, polycrystalline, amorphous, and epitaxial. The materials used in the CVD process include silicon, SiO_2, silicon carbide, silicon nitride, silicon oxynitride, silicon–germanium, and carbon nanotubes. Silicon is generally used in the production of a wafer used in microelectronic industry. The thin film of polycrystalline silicon is produced from either pure silane (SiH_4) gas or a silane solution and the involved chemical reaction is as follows:

$$SiH_4(g) \rightarrow Si(s) + 2H_2(g)$$
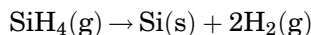
Synthetic diamonds can also be produced using the CVD technique.

The CVD process can be enhanced using various techniques involving plasma, radio waves, and microwave. Plasma refers to a partially or fully ionized gas and is often used in processes, eg, welding, plasma spraying, hazardous waste destruction, and semiconductor processing. Thermal plasma CVD or plasma-assisted CVD (PACVD) can be used to generate hard coatings on a substrate. Particularly, PACVD can be used for coating orthopedic and dental implants made of plastics, metals, and various natural materials with amorphous diamond-like carbon substance that is chemically inert. This coating prevents bacterial colonization of the tissues. During PACVD, the radio waves may be used to strip off the electrons from coating material and charge it positively. The charged coating materials would adhere to the substrate faster and stronger via static attraction. Microwave plasma enhanced CVD (MPECVD)

is another CVD technology for producing thin films. This method is attractive due to its fast deposition rate; however, for large-scale applications the inconsistency of the film thickness and thin-film properties may be significant.

Atomic layer deposition (ALD) is another technique that is used to grow thin film onto substrates of various compositions ranging from ceramics to insulators. The main difference between CVD and ALD is that ALD uses two half reactions of the CVD process, and hence, the precursor materials are segregated during ALD coating and conformal, pinhole free thin film of controlled thickness (1–500 nm) is formed.

Other Methods. A number of reaction mechanisms are being developed to synthesize functionalized nanoparticles (5). Traditionally, various particles and catalysts are synthesized via wet chemistry. A flame spray pyrolysis (FSP) process has been developed as an alternative to the traditional vapor-fed flame reactors due to its flexibility of precursors. The use of flame method allows the production of aerosols or highly pure nanosized catalysts, eg, $Pt/Ba/Al_2O_3$, that can be used for NO_x reduction in lean-fuel engines. A plasma reactor and a radiation-chemical method are also suggested for the production of various nanaoparticles.

Once particles are formed, their surfaces may be modified by either a passive probe generating surface indentation or by active probes that employ electrical, chemical, optical, or diffusion processes for surface modification.

5. Particle Processing Systems

Particle processing systems for dynamic particle flows are categorized according to the system requirements and characteristics. The same system can also serve multiple purposes of particle processing, depending on the operation conditions and particles involved. For example, a fluidized bed may be operated in the dense-phase fluidization regime for particle mixing or coating, while at higher gas velocities, it can be operated in the circulating fluidization regime for dispersion of fine particles or particle transport. In what follows, particle processing systems with respect to transport, separation, and fluidization are discussed in detail.

5.1. Transport Systems. Solids can be transported from one location to another via various means, including (*1*) pneumatic conveying, in which solids are transported in a pipe or channel by gas flow through blowing or suction; (*2*) gravity chutes, where solids transport downward by gravitational force; (*3*) air slides, where solids, partially suspended in a channel by the upward flow of air through a porous wall, flow at a small angle to the horizontal; (*4*) belt conveyors, where solids are conveyed horizontally, or at small angles to the horizontal, on a continuous moving belt; (*5*) screw conveyors, in which solids are transported in a pipe or channel by a rotating helical impeller; (*6*) bucket elevators, in which solids are carried upward in buckets attached to a continuously moving vertical belt; and (*7*) vibratory conveyors, where solids flow is activated by jigging action provided by angled spring supports.

Hoppers and Standpipes. Granular materials flowing by gravity are routinely processed in a nearly packed condition through hoppers and standpipes

(8). Hoppers are funnel-like vertical columns, and standpipes are vertical or inclined pipes of constant cross-sections. The onset and continued motion of powder in a hopper is due to stress failure in powders. Hence, the study of a hopper flow is closely related to the understanding of stress distribution of powders in a hopper. Flow-promoting devices, eg, vibrators and aerating jets, are commonly used to prevent the stop of powder flow or to reinitiate the flow of stagnant granular materials.

In a standpipe or downcomer flow, solids flow downward against a gas pressure gradient due to the gravitational force. Although the gas flow with respect to the downward-flowing solids is in the upward direction, the actual direction of flow of gas relative to the wall can be either upward or downward. Solids fed into the standpipe are often from hoppers, cyclones, or fluidized beds. The outlet of a standpipe can be simply an orifice or be connected to a valve or a fluidized bed, with a discharge corn flow region near the outlet. There can be aeration along the side of the standpipe. Note that the downward transport may also be achieved with higher pressure at the top. In this case, the solids transport is referred to as a discharged flow.

For a standpipe system, different flow patterns of steady-state flows may exist, depending on the ranges of operational parameters of the system. This phenomenon is known as the steady-state multiplicity. There are four possible flow regimes for standpipe flows, including (*1*) a moving-bed flow mode throughout the standpipe; (*2*) a combined suspension flow and moving-bed flow begins, with the transition location above the discharge cone; (*3*) a combined suspension flow and moving-bed flow begins, with the transition location inside the discharge cone region; and (*4*) a suspension flow without moving bed. With side aeration, the multiplicity of flows in the standpipe becomes much more complicated. For example, for a single aeration point, the possible number of flow regimes increases to 12.

Pneumatic Transport.   Basic parts of a pneumatic conveying system include pipes of various inclination, bends, branches, adaptors, and valves. Materials to be conveyed are usually dry and readily free-flowing. Some sluggish and damp materials can also be free-flowing with proper aeration. It is often operated in a dilute phase and the flow regime varies with the solids concentration. Multiple flow regimes may coexist in a given operational system. The advantages of pneumatic conveying include extreme flexibility in routing and spacing, safe working conditions, and low maintenance cost. Its disadvantages include relatively high power consumption compared to that of other bulk solids transport systems and significant wearing and abrasive effects due to high collision velocity of solids in a dilute-phase conveying systems. The transport phenomena associated with the pneumatic conveying of solids are complex, and, therefore, special requirements are needed in the design and operation of those systems. Variables governing the phenomena encompass the gas velocity, characteristics of the solids (size, density, distribution, and shape), solid loading, pipe size and configuration, solids feeding device, and transport direction (12).

Pneumatic conveying systems can be classified on the basis of the angle of inclination of pipelines, operational modes (ie, negative- or positive-pressure operation), and flow characteristics (ie, dilute or dense-phase transport; steady

or unsteady transport). A practical pneumatic conveying system is often composed of several vertical, horizontal, and inclined pipelines (2).

In a horizontal pipe-flow at a given gas-flow rate, the following flow patterns sequentially occur as the particle loading, defined as the mass flow ratio of particles to gas, increases: (*1*) dilute suspension flow; (*2*) sedimentation of particles and dune formation; (*3*) stratified flow; (*4*) plug flow; and (*5*) moving-bed flow at relatively high gas velocity or solid ripples traveling along the top of a stationary solid layer at relatively low gas velocity. In vertical pneumatic transport, particles are always suspended in the gas stream mainly because the direction of the gravity is in line with that of the gas flow. Hence, to transport the same solids mass flow rate in a suspended flow, it takes lower gas velocity for upward vertical conveying than for horizontal conveying. Inclined pipelines require the highest gas velocity to convey the same amount of solid materials when compared to both vertical and horizontal conveying. In this case, gas flow has to overcome the forces associated with horizontal conveying and the tendency of materials to slide back down the incline.

The flow regimes for a pneumatic conveying system can generally be determined in terms of the variation of the pressure drop per unit length with the superficial gas velocity and the solids mass flux (12). The minimum pressure drop point usually marks the transition from the dense to dilute flow regimes. For vertical conveying, the choking phenomenon may also occur, depending on the pipe size and particle properties. For horizontal conveying, the saltation phenomenon will take place at the minimum pressure drop point for coarse particles, where particles start settling at the dilute and dense flow transition. For fine particles, the saltation phenomenon takes place at gas velocity higher than that for the minimum pressure drop point.

Dispersers.   Dispersers are devices to disperse particles into flow streams and are often used to enhance the flowability of particulate flows throughout the transport systems. Typical dispersers include nozzle jets, ejectors, inhalers, and rotating-blade dispersers. Nozzle jets are commonly used for mixing enhancement by jet-induced entrainment, as well as particle dispersion by the strong jet shearing in the jet boundary. Most ejectors and inhalers are venturi jets, in which the lowest static pressure occurs at the throat section while the flow velocity reaches its maximum. Through a small opening located in the venturi throat section, ejectors and inhalers are able to suck the particulates or aerosols from a storage tank into the venturi jet and disperse the particles (11). A rotating-blade disperser is commonly used to breaks apart solid clusters in a liquid via high shear forces and impacting forces generated by the rotating blades. Another common-type rotating disperser uses spinning magnets controlled in an alternating-current magnetic field to break the particle clusters or dissolve particles in a liquid.

5.2. Separation Systems.   Separation processes are achieved by application of the principles involving gravitational settling, centrifugation, electrostatic effects, filtration, and wet scrubbing. The typical separation devices corresponding to these principles are settling chambers, rotary-flow dust separators, electrostatic precipitators, filters, and scrubbers. Other common separators include sieves, cascade impactors, and segregators that were discussed earlier.

Most of the separation devices can be applied to different multiphase systems including gas−solid, liquid−solid, and three-phase flows.

Gravity Setting Chambers.   The most classical method for solids removal from a stream is gravity settling, in which the natural gravitational force separates particles from their carrying medium on the basis of the difference in material density or inertia. Although gravity settling devices have the advantages of simple structure and economical operation, their development has been nearly halted by the low collection efficiency and the large collection chamber requirement compared to that of other separators. The gravity settlers are typically used as precleaners to remove large particles and one of its typical applications is in wastewater treatment. A slight variation of the gravity settling chamber, known as an elutriator, is also frequently used in industry.

Rotary Flow Separators.   In a rotary flow dust separator, the rotating flow of the particulate suspension can be initiated as a result of the design of the separator, eg, the tangential inlet of the separator, the guide vanes at the inlet, and relative rotating cylinders. As a result of the rotating flow, the particles are subjected to a centrifugal force that is usually at least two orders of magnitude greater than the gravitational force. Thus, even light particles can be easily directed toward the wall by the centrifugal force and collected in the dust bunker, while the clean fluid exists through the separator outlet.

Typical rotary flow separators include the tangential inlet cyclones, axial flow cyclones, and the rotating cylinder separators. The cyclone dust collector is the simplest with no moving parts and ease in maintenance. In spite of the simple structure, the centrifugal force on the solids in the cyclone dust collector can easily reach 300−2000 times the gravitational force, and high separation efficiencies can thus be achieved. An axial flow cyclone with guide vanes has relatively lower separation efficiency compared to that of the tangential inlet cyclone. However, due to its slower rotating gas flow caused by the guide vanes, the coaxial structure of the outlets for solids and fluid flow in the cyclone with guide vanes are effective at preventing the reentrainment of the solids that may occur in a tangential inlet cyclone. The advantages of cyclones include low operating costs, reliability, and suitability for high temperature operations. In rotating cylinder separators, eg, the rotex centrifugal separator, the dust-laden gas flows through the rotating cylinders and starts rotating by the effect of wall friction at the cylinders. The separation of particles is achieved by the relative inertia between gas and particles and by the effect of gravity.

Filters.   Filtration is a physical separation, whereby particles are removed from the fluid stream and retained by the filters when the particulate suspension passes through a single-layer screen, a multiple-layer screen, or a porous, permeable medium. Three basic collection mechanisms involving filters are inertial impaction, interception, and diffusion. Inertial impaction and interception are the dominating mechanisms for collection of large particles, while collection by diffusion is very important for fine particles. This separation technique is simple and has a high efficiency in collecting particles of all sizes. However, in this type of separation method, a high pressure drop may develop as a result of the accumulation of collected particles in the filter, which may yield high energy consumption and require high material strength of filters for the operations.

Filtration techniques can be classified into cake and depth filtration. In cake filtration, particles are deposited on the front surface of the collecting filter. Examples of filters in cake filtration include fabric filters, sieves, nuclepore filters, and membrane filters. In depth filtration, particles flow through the filter and are collected during their passage. Filters for depth filtration include packed beds, meshes, fluidized beds, and glass-fiber filters. In both cake and depth filtration, continuous particle collection increases the flow resistance through the filter, and, thus, the collection efficiency decreases. Efficient operation of the filter requires periodic removal of the particles deposited on the filter or replacement of the filter. Filtration is constantly combined with other collection mechanisms, eg, centrifugal sedimentation, electrostatic precipitation, and van der Waals deposition often as a final step of the separation process.

Electrostatic Precipitators. An electrostatic precipitator separates suspended, charged particles from a gas stream using electrostatic force. Since the separation force is directly applied to the particles without the need of accelerating the gas phase, an electrostatic precipitator usually requires much less hydraulic power than other separation systems. Hence, an electrostatic precipitator is widely recognized as an important technique of gas–solid separation (eg, fly ash removal from flue gas of coal-fired power plants). This technique is characterized by a low pressure drop, relative high collection efficiency for fine particles, and high adaptability to a wide variety of effluents, either wet, dry, or corrosive.

The complete process of particle removal by electrostatic precipitation commonly includes three steps: (*1*) particle charging; (*2*) particle migration in an external electric field; (*3*) particle discharging and collection. Particles in a gas stream can be charged naturally through triboelectric charging. However, to reach high collection efficiency in an electrostatic precipitator, the particles are typically artificially charged to a saturated degree by passing through a corona discharge area where the gas is highly ionized. When particles are exposed to unipolar ions in an electric field, impacts of ions and particles take place as a result of two basic mechanisms: field and diffusion charging. In most cases, for particles inside electrostatic precipitators, the saturation charge is attained within a second. The charged particles migrate toward the collecting electrodes in the applied electric field by the Coulomb force. Upon contact with the collecting electrodes, the particles lose their charges and thus can be removed either by adhesion to the collecting surface or by sliding into the discharge hoppers located beneath the electrodes.

Typical geometric shapes of the corona dischargers in electrostatic precipitators are either thin metal wires or metal needles, whereas collecting electrodes are generally plates or cylinders. Electrostatic precipitators may thus be divided into two types, cylinder- and plate-type. Cylinder-type electrostatic precipitators may achieve collection efficiency as high as 99.9%. Plate-type precipitators, commonly used for dry particle-laden gas with large flow rates, can reach a collection efficiency of 95%.

Wet Scrubbers. A wet scrubber uses liquid droplets to remove fine dust in a gas stream. The collected particles and liquid droplets then form a slurry that flows to the slurry collection chamber. Almost all particle-separating devices can be converted into wet scrubbers by adding liquid spraying systems. Three

types of commonly used scrubbers are the spray chamber, cyclonic scrubber, and venturi scrubber. The advantages of wet scrubbing include low pressure drop, relatively high efficiency for fine particle collection, no particle reentrainment, and possible removal of some gases pollutants simultaneously by using chemical solutions as the collecting liquid (eg, lime spray dryer and amine scrubbing). The disadvantage of this separation technique is the necessity for the treatment of the wet sludge generated from the wet scrubbing process.

5.3. Fluidization Systems.   Contact schemes of gas–solid systems can be classified on the basis of the state of solids motion. For a fixed-bed system, the fluid at a low velocity merely percolates through the voids between packed particles while the particles remain motionless. With an increase in the fluid velocity, particles move apart and become suspended; the bed then enters the fluidization state. In fluidized beds, particles are fluidized and move in a circulatory motion within the bed. The fluidization behavior of the particles is determined by their physical properties and the classification of particles in terms of their fluidization behavior was presented in Fig 1. Most fluidized beds are designed against gravity, but they can also be designed in the presence of other field forces, eg, vibrational, acoustic, centrifugal, and magnetic forces. These additional forces are particularly important for the fluidization of highly cohesive particles including various nanoparticles. In the following sections, different fluidization systems are introduced based on the flow regimes and phases involved.

Packed Beds.   A packed bed is a tube or pipe filled with a packing material, which can be a variety of shapes and sizes. Packed beds (ie, fixed-bed or packed columns) are typically utilized in chemical processes to enhance the contacting efficiency among gas, liquid, and/or solid phases. Its application includes a distillation column, a trickle-bed reactor, and a scrubber, as well as a lab scale chromatography system. A packed bed also represents the limiting case of the multiphase flows including gas–solid fluidized beds. Thus, the Ergun equation that is employed to obtain the pressure drop of a packed bed when given the physical properties of fluid, the fluid velocity, and the packing size, can also be used to predict the minimum fluidization velocity of the gas–solid fluidized bed (8).

Gas–Solid Fluidized Beds.   As the gas velocity is increased beyond the minimum fluidization velocity, a fixed bed (ie, packed bed) becomes a fluidized bed. For a given fluidization system, a dense-phase fluidization occurs at low gas velocities, whereas at higher gas velocities, lean-phase fluidization is observed. Dense-phase fluidization regimes include particulate fluidization, bubbling fluidization, and turbulent fluidization with ascending gas velocities. Bubble-like voids among the suspended particles in fluidized beds represent the majority of the operating interests, although the beds may also be operated without bubbles for Group A particles (ie, particulate fluidization). Dense-phase fluidization also encompasses the spouting, slugging, and channeling regimes or conditions of operation. Spouting is often used in a drying process for a particulate system containing Group D particles. The particle mixing in a spouted bed is induced by the axial spout instead of a gas distributor generally used in fluidized beds. Slugging refers to the fluidization regime that is characterized by the presence of bubbles or slugs with sizes comparable to the bed diameter, whereas

channeling is caused typically by aggregation effects of cohesive (Group C) particles due to interparticle contact forces. Both slugging and channeling are not desired for operating fluidization systems, since they reduce the contact between the gas and solids particles.

As the gas flow rate increase beyond the point corresponding to the disappearance of the bubble–void phase, a drastic increase in the entrainment rate of particles occurs such that a continuous feeding of particles into the fluidized bed is required to maintain a steady solids flow. Fluidization at this state, in contrast to dense-phase fluidization, is denoted lean-phase fluidization. There are two flow regimes that encompass lean-phase fluidization: the fast fluidization regime and the dilute transport regime. Due to short contact time between the gas and solid phases, fast fluidization is often used for process applications involving chemical reactions (eg, FCC and coal combustion). Dilute transport regime is used during pneumatic conveying of solids (8).

A typical gas–solid fluidized bed consists of a distributor, gas–solid separator (eg, cyclone and dipleg), heat exchanger, expanded section, and baffles. For a circulating fluidized bed (CFB) operating under fast fluidization regime, the main vertical section of the bed is called a riser, while a downer and solids flow control device are added to maintain the solids flow into the riser of the CFB.

In a riser, solids are transported upward against gravity by an incoming gas. A riser flow is different from the vertical pneumatic transport. A riser flow operating under the fast fluidization regime is characterized by a heterogeneous flow structure, typically with a downward solids flow in the pipe wall region (known as back mixing) and/or a dense-phase flow at the lower section of riser. On the other hand, the vertical pneumatic transport in the dilute transport regime is characterized by a homogeneous flow structure with little back mixing. For a small column with relatively large particles, a sharp collapse of a relatively dilute suspension of the fast fluidization to a relatively dense suspension can occur when the solids circulation rate reaches the saturation solids carrying capacity at a given gas velocity. For smooth operation of CFBs, it is important to maintain the solids circulation rate below the choking level (2).

Gas–Liquid–Solid Fluidized Beds and Slurry Bubble Columns. Gas–liquid–solid fluidized beds are also called three-phase fluidized beds. The classification between the three-phase fluidized bed and the slurry bubble column is made based on the sizes of the particles involved. Slurry bubble columns operate with the particles in the range of 5–200 μm, while the three-phase fluidized beds generally involves relatively larger particles. The flow regimes associated with the operation of the gas–liquid–solid fluidized beds and slurry bubble columns are similar to those of gas–solid fluidized beds. The physical properties of each phase (ie, gas, liquid, and solid phases), fluid velocity, reactor geometry, distributor design, operating pressure, and temperature all affect the fluidization behavior of these multiphase systems.

Numerous applications of gas–liquid–solid fluidization systems exist that vary in size from bench to commercial scale. In these applications, the individual phases can be reactants, products, catalysts, or inerts. For example, all three phase are either reactants or products as in coal liquefaction. The gas and liquid phase can be either reactants or products and the solid can be a catalyst as in hydrogenation of α-methyl styrene in a slurry of alumina-supported palladium

catalyst. Two phases can be reactants or products and the third phase can be inert as in ammonia scrubbing by a boric acid solution. The phases can be neither reactants nor products as in purely physical processes, eg, air humidification. In addition, slurry bubble columns are widely used to produce nonpetroleum-based liquid fuels from sources, eg, natural gas, coal, and biomass via Fischer–Tropsch synthesis (1).

5.4. Other Systems. Other particle processing systems include devices for particle size reduction or comminution (eg, crusher, ball milling, jet attrition, and grinders), devices for particle size enlargement (eg, coating and granulation), mixers, and case and molding devices.

6. Modeling and Computation

6.1. Hydrodynamics Modeling. For particle suspensions, three distinct regimes can be identified, namely, the macroviscous, transitional, and grain inertia regimes. In the macroviscous regime, the fluid viscosity dominates the motion of solids, and the shear stress is linearly related to the shear rate. The particle motion in this regime can be described by using either the continuum or the trajectory modeling. In the grain inertia regime, granular flows occur where the particle motion is largely governed by particle–particle interactions, and the shear stress depends on the square of the shear rate. The transition regime falls between the macroviscous and the grain inertia regimes. The study of grain inertia flows may be conducted in light of the kinetic theory modeling, where the interstitial fluid plays little role in the momentum transport of solids.

Multiphase Continuum Theory. The multiphase continuum theory, also known as the Eulerian continuum method or the multi-fluid approach, considers each dynamic phase in a particulate flow as a pseudocontinuum phase so that the basic flow properties, eg, pressure, mass fluxes, concentrations, velocities, and temperatures of each phase can be described in an Eulerian coordinate system. The Eulerian continuum approach is basically an extension of the mathematical formulation of the fluid dynamics for a single phase to a multiphase flow.

Since neither the fluid nor the particle phase is actually continuous throughout the system at any moment, ways to construct a continuum of each phase have to be established. The volume averaging theorem is typically used to define the pseudocontinuum properties of each phase in a multiphase flow, and thereto yield the volume-averaged governing equations of phase transport. Note that the pseudocontinuum phase in a multiphase flow should be regarded as compressible because of the nonuniform behavior of the volume fraction distribution of the phases even though the fluid or the particle material may be incompressible. To account for the turbulence effects, time averaging is constantly adopted after the volume averaging.

The turbulent transport properties of the fluid phase can be determined by turbulence models, eg, the mixing length and $k-\varepsilon$ model, with some modifications accounting for the compressibility of the pseudocontinuum phase and phase interactions. The turbulent transport properties of the particle phase under the particle–fluid interactions can be determined by turbulence modulation models, eg, the Hinze–Tchen model or the $k-\varepsilon-k_p$ model. In dense

suspensions, the collisional transport properties of the particle phase can be estimated assuming a direct analogy of interparticle collisions to that of gas molecules and using the kinetic theory of gases. In such an approach, the modifications due to the inelastic collision behaviors of particles and their couplings with viscous fluids are constantly required.

Note that, in most Eulerian continuum models, it is assumed that the basic form of the Navier–Stokes equation can be applied to all phases. This assumption may not be true, especially for some dense suspension cases where the particle phase behaves as a non-Newtonian fluid or the fluid phase itself is non-Newtonian. In these cases, a simple extension of the Navier–Stokes equation may not be appropriate.

Lagrangian Trajectory Method. The Lagrangian approach, also known as trajectory modeling, provides a direct description of particulate flows by tracking the motion of individual particles. In trajectory modeling, the motion of a particle can be expressed by ordinary differential equations in Lagrangian coordinates. Consequently, the particle velocity and the corresponding particle trajectory can be solved by directly integrating the Lagrangian equation of the particle. Therefore, the Lagrangian approach is convenient to reveal the discrete and transient nature of the motion of particles.

Typical Lagrangian approaches include the deterministic trajectory and the stochastic trajectory method. The deterministic trajectory method neglects all the turbulent transport processes of the particle phase, while the stochastic trajectory method takes into account the effect of flow turbulence on the particle motion by considering the instantaneous fluid velocity in the formulation of the equation of motion of particles. To obtain the statistical average of the variables in the equations, statistical computations based on techniques, eg, the Monte Carlo method, need to be performed.

In order to solve the Lagrangian equation for a moving particle, the dynamic behavior of the fluid phase and other particles surrounding this moving particle should be predetermined. In this regard, the behavior of the fluid phase is simulated by the Eulerian method. Since the fluid flow and the motion of all particles are coupled through fluid–particle and particle–particle interactions, a large number of iterations are typically required in order to obtain converged solutions for all phases.

Granular Flow Theory. In a particle processing system dominated by the interparticle collisions, the stresses and other dynamic properties of the solid phase can be postulated to be analogous to those of gas molecules. The physical condition of the kinetic theory of gases can be described by elastic collisions of monodispersed spheres with the Maxwellian velocity distribution in an infinite vacuum space. Therefore, for an analogy between particle–particle interactions and molecular interactions to be directly applicable, the following phenomena in fluid–solid flows should not be regarded as significant in comparison to particle–particle interactions: the fluid–particle interactions involving velocity-dependent and pressure-dependent forces, energy dissipation due to inelasticity and friction in particle collisions, and particle–wall interactions. The approach that rigorously followed the kinetic theories of gases for solid particles, however, came to a halt as a result of the complexity surrounding the direct application of the Boltzmann equation in accounting for interparticle collisions.

An alternative approach using simplified kinetic theories of gases based on mechanistically derived or intuitive relationships in place of the Boltzmann equation has been viewed as viable. It is assumed that collision among particles is the only mechanism for the transport of mass, momentum, and energy of the particles. For a dense system of hard, smooth, and elastic spherical particles, a dense-phase transport theorem can be derived based on the analogy of the kinetic theory of dense gases. The fundamental quantities that are conserved in a collision are the mass of a particle and each component of the total momentum of the colliding particles. Thus, conservation equations can be obtained by the use of the transport theorem. Although the energy equation can also be derived from the transport theorem, the total kinetic energy of the colliding particles is not conserved because of energy dissipation in the form of heat loss. The energy dissipation due to inelastic collisions can also be included in the model despite the elastic collision condition dictated by the theory. For equation closure, additional constitutive relations, which can be obtained by using the kinematic argument of the collision and by assuming the Maxwellian velocity distribution of the solids, are needed. In a typical granular theory modeling, five governing equations are obtained from mass, momentum, and energy conservation. The five unknowns to be solved are granular volume fraction, granular velocity, and granular temperature (defined as translational fluctuation energy of granular velocity). Inelastic collision is characterized by the restitution coefficient, which is determined empirically for most granular flows.

According to the study on the hydrodynamics of rapid granular flow consisting of smooth, inelastic hard spheres into vacuum performed using three different methods: both (*1*) analytical; (*2*) computational treatments of a hydrodynamic model; and (*3*) by Discrete Element Method simulation. Cluster formation did not have significant effect on the hydrodynamic behavior of the flow, and hence suggested that the combination of the hydrodynamic model and the CFD algorithm may be effective at solving other related problems.

6.2. Direct Numerical Simulation.   The numerical simulations provide insights into the physical mechanisms of the particle–turbulence interaction in dispersed multiphase flows (7). In what follows, different DNS methods are discussed in detail.

Lattice–Boltzmann Method.   The Lattice–Boltzmann method (LBM) is a relatively new method that has been developing rapidly in the last 10–15 years. The concept of LBM is based on the mesoscopic kinetic description of fluid. Under the incompressible limit, it can be shown that the LBM recovers the Navier–Stokes equation by the Chapman–Enskog expansion.

Similar to the traditional CFD techniques, the particulate flows in the LBM framework can be modeled either by direct numerical simulation, or by using the Lagrangian particle approach. In the former, the size of the particle is much larger than the lattice spacing, and the flow in the vicinity of the particle is solved directly. The fluid–particle interactions are calculated from the momentum exchange across the solid boundary, usually by employing bounce-back of the distributions, which leads to no-slip condition. Closure relations for the drag on the particles can be obtained by simulating the motion of a cluster of particles in the flow. In this case, the main advantage of LBM is its easy

implement of the boundary condition. For the latter, the size of the particle is much smaller than the lattice spacing, and the fluid–solid interactions are modeled using correlations. These correlations can either be obtained experimentally, or by using direct numerical simulations, eg, the LBM mentioned above. In this case, compared to traditional CFD techniques based on the Navier–Stokes equation, LBM has the advantage of simple algorithm, easy implementation and ease of parallelization.

Hard- and Soft-Sphere Model. The discrete element method (DEM) is a discrete particle simulation technique that calculates the trajectory of and transient forces on each individual particle. Two types of particle models are commonly used in DEM simulations, the hard-sphere and the soft-sphere model. In the hard-sphere model, the particles interact with each other via instantaneous binary collisions. In the soft-sphere model, the particles are allowed to deform, and elastic, plastic, and friction forces are used to calculate the particle motion by Newton's law. Multiple particle contacts are also allowed in soft-sphere models. As the result, the soft-sphere models are capable of modeling quasistatic systems, while the hard-sphere models are more useful for rapid granular flows. The DEM simulations have been used extensively to study various phenomena, eg, particle packing, mixing, and transport. The DEM is also often used in combination with CFD to study particle–fluid flows, eg, fluidization.

Molecular Dynamics Simulation. A molecular dynamics simulation calculates the time-dependent behavior of a particle system at the atomistic level. Molecular dynamics simulations are based on the force field for molecules, which is strongly dependent on the particle positions. The particle velocities within the system also affect the force field for molecules. The particle interactions are typically expressed in forms of potential energy of interactions. For a pair of interacting particles, there can be long- and short-range interactions. Typical long-range or nonbonded interactions include the Lennard-Jones interaction and Columbic interaction. Typical short-range or bonded interactions include the covalent interaction, the bond-angle and the dihedral interaction, which represent strong chemical bonded interaction that are not created or destroyed during a simulation. Based on the statistical mechanics and Newton's law of motion, iterative calculations of all particles for their positions and velocities within the system can be made. Molecular dynamics simulations then yield detailed information on the fluctuations and conformational changes of molecules that make up a solid particle or particle system.

Another interesting branch of dynamic simulation is the atomistic simulation, which consists of two components: dynamics simulations of structure evolution using force field or interatomic potentials, and statics determination of energetics using the density functional theory. The dynamics simulations allow the investigation of atomic mechanisms of structure evolution of both molecules and solids surfaces. Complementing the dynamics simulations, the statics determination provides validation–calibration to selected configurations from the dynamics simulations. Atomistic simulation can be used to investigate the interaction of a molecule with a solid surface of varying crystalline orientations, roughness, or chemical compositions.

6.3. Common Commercial Codes. A number of computational codes including FLUENT, FLOW-3D, and ABAQUS are commercially available to model and simulate a wide array of industrial applications and physical processes ranging from a 10-m diameter Fischer–Tropsch slurry bubble column reactor to blood flow. These commercial codes allow engineers to gain valuable insight into process units that are difficult to explore in order to better design and improve the chemical processes.

FLUENT can be used to investigate the dynamic behavior of interpenetrating fluids or phases based on the Eulerian continuum approach or a more economical mixture model. Both models can also be applied to granular flows. Other multiphase models typically used in FLUENT include the discrete-phase model (DPM) available for systems, eg, spray dryers, liquid fuel sprays, and coal furnaces. The volume of the fluid model is capable of predicting the interface of free surface flows, eg, ocean waves, while the cavitation model is applied to model hydrofoils, pumps, and fuel injectors. FLUENT employs unstructured grid technology, and thus, different geometric shapes of elements can be selected for the generation of the grid: quadrilaterals and triangles for two-dimensional (2D) simulations and hexahedra, tetrahedra, polyhedra, prisms, and pyramids for three-dimensional (3D) simulations.

FLOW-3D is also a very useful simulation and modeling tool for multiphase flow systems. Particularly, it is specialized in solving time-dependent (transient) free surface problems, while it can also be applied to confined and steady-state flows. FLOW-3D uses the improved Volume of Fluid (VOF) model called TruVOF to investigate free surface in order to provide greater accuracy of boundary conditions and the tracking of interfaces. There is no need for additional modules for meshing or postprocessing, since an integrated graphical user interface of FLOW-3D is all-inclusive. FLOW-3D has features, eg, free gridding that incorporates simple rectangular grids with flexibility of deformed, body-fitted grids, and multiblock meshing approach that provides further flexibility and efficiency to the finite difference meshing technique. The Fractional Area Volume Obstacle Representation (FAVOR) method offers easier modeling fluid flow in complex geometry.

ABAQUS is another well-known commercial code, which focuses on finite element analysis. ABAQUS features direct access to CAD models, meshing, and visualization. It is used to solve a wide range of finite element problems related to both static and dynamic manufacturing processes (ie, drop test and crushing) with a variety of contact and nonlinear material options. ABAQUS can also readily be integrated with third-party software, eg, plastic injection modeling analysis.

Other commercially available computational codes include the following (alphabetical listing): ACRi, ARSoftware, AVL FIRE, CFD-ACE+, CFD-FAS-TRAN, CFD++, CFdesign, CFX, Coolit, COSMIC NASA, COSMOSFloWorks, FBED, EFD.Lab, EFD.Pro, EFD, Flo++, FLOTRAN, FLOTHERM, FLOVENT, FOAM, KIVA, KSNIS, LAMDA, Linflow, LS-DYNA3D, NUMECA, PAM-FLOW, PAM-FLUID, PFDReaction, PHOENICS/CHAM, RADIOSS-CFD, Simulog, STAR-CD, V5, VECTIS, and VISCOUS. Additional software packages, eg, Tecplot and KINetics are used to support the CFD codes for postprocessing and for solving detailed chemical kinetics, respectively.

7. Flow Measurement Techniques

The hydrodynamic behavior of the particulate flows can be quantified through direct visualization or employing various flow measurement techniques. To visually observe the movement of solids and bubbles from the outside of a process unit, eg, a gas–solid fluidized bed, a 2D fluidized bed is commonly used. From analyzing the data captured by the cine photography or video imaging, the bubble flow behavior including the bubble shape, bubble size, and bubble rise velocity with respect to the particulate phase can be quantified. However, due to the wall effect, questions remain if the information obtained in the 2D flow systems can be directly related to the 3D flow systems. Thus, a large number of measurement techniques including both the intrusive and nonintrusive methods have been developed to investigate the flow behavior of gas, liquid, and solids in the multiphase systems. These measurement techniques can be applied to various particulate flow systems, and here their applications to gas–solid fluidized beds are discussed in detail as an example.

7.1. Intrusive Methods

Probes.   The intrusive probes that have been used to measure particulate flows include capacitance probes, optical fiber probes, endoscopic probes, and pressure transducers. Capacitance probes are utilized to measure the local solids concentration based on the local dielectricity of the gas–solids suspension. The technique has been applied to measure the bubble volume fraction, bubble length, and bubble rise velocity in gas–solid fluidized beds. With the capacitance probe, at low gas velocity, the bed exhibits the two-phase flow structure with low solids concentration inside of the bubble, while the bubbles break up into smaller ones with relatively high solids concentration at high gas velocity. However, the precise calibration is necessary for this technique to be applied in the gas–solid fluidized beds particularly at low gas velocities. A needle-type capacitance probe has also been developed to provide minimal interference with the flow during the study of the bubble flow behavior in the gas–solid fluidized bed. The capacitance probe is, however, sensitive to electrostatic effects, difficult in defining the measuring volume, and influenced by the changes in temperature and relative humidity.

The optical fiber probe usually consists of two portions. One is for transmitting light into the bed from the light source and the other is for detection of the light either reflected by solids particles or without adsorbed, by solids in the bed. With this technique, the measuring volume of the optical fiber probe is often not well defined. Further, the measuring volume varies with the solids concentration in the bed, introducing error into the measurement by this technique. A reliable and precise calibration is essential for this technique. By positioning two optical fiber probes one above the other, the bubble rise velocity in the multiphase flows can be measured, as well as the local bubble–void and solid fractions. The optical fiber probe technique is also used to study the bubble characteristics including bubble size distribution and bubble rise velocity distribution in a multiphase flows.

The image carrying fiber optic probe (endoscopic probe) has been used to study the particle ejections by the bubble eruption at the surface of a bubbling

fluidized bed, while the pressure drop measurement has been used to study the bubble flow behavior in the gas–solid fluidized bed together with the statistical analysis techniques. The pressure transducer can be either positioned on the wall of the bed or immersed in the column. However, the pressure drop can only provide the overall information inside of a fluidized bed. The bubble flow, bubble coalescence and breakup, bubble burst at the top surface, bubble formation at the distributor, can all generate the pressure variations in the bed.

It is evident that probe measurement would interfere with the hydrodynamic behavior in the multiphase flow systems. The bubble might be broken, accelerated, or elongated by the immersed probe. Although tiny probes could minimize the intrusive effect, the probes are easily damaged. The accurate conversion of the chord length distribution-to-bubble size distribution is also challenging as the bubble shape and size distribution vary with location measured.

Tracer Injections.   Various types of tracers, eg, the colored tracer, ferromagnetic, fluorescent, and radioactive tracer were been used to measure the flow properties (eg, solids mixing). Tracer particles move along with the particles in order to track their movement. Thus, it is very important that tracer particles have the same density, size, and shape as the particles in interest. The method using colored tracers is one of the simplest methods of the tracer techniques and generally provides qualitative information on solid mixing. But it can be time consuming to separate the particles according to their color during the measurements. Porous catalyst particles impregnated with ferromagnetic materials are also used as tracers. In this technique, two concentric loops are installed around the process unit and the signal detected by the inner loop in the presence of the external electrical field originated from the outer loop, provides information on particle flows. The advantage of this method is the ease of tracer particle extraction from the postinjection mixture by magnetic separation. The technique using fluorescent tracers employs the characteristic of the phosphorescent material that becomes fluorescent for a short period of time after being excited. This method can be performed by injecting tracer particles impregnated with fluorescing materials, or the entire system can be made up of phosphor particles. In the latter case, light is introduced as an impulse, which controls the amount of particles becoming fluorescent tracer particles. The light emitted by the fluorescent tracer particles is detected by optical fiber probes and the output signal is used to quantify the axial and radial solids mixing behavior of a multiphase flow system. Radioactive tracers are also used in similar manner.

7.2. Nonintrusive Methods.   The major advantage of the nonintrusive techniques is no interference with the flow. The information provided by the nonintrusive techniques is usually the cross-sectional solids concentration profile or an image in a given volume, whereas the intrusive techniques only allow localized measurements. The nonintrusive techniques that can be used to investigate gassolid flows include X-ray, γ-ray, Positron Emission Tomography (PET), Radioactive Particle Tracking (RPT), Magnetic Resonance Imaging (MRI), Particle Image Velocimetry (PIV), and Electrical Capacitance Tomography (ECT). These techniques have been used to measure the properties of gas–solid fluidized beds.

Tomographic Techniques. The X-ray technique usually consists of the X-ray source to generate the X-ray beam to pass through a multiphase flow, image intensifier to produce an image that can be visually observed, CCD video camera to capture the image, and the image analysis system. The 2D X-ray is difficult to distinguish the bubbles from the particulate phase at different depths, and thus, is mostly used to investigate the flow behavior of a single bubble. Recently, the X-ray Computer Assisted Tomography (CAT) has been developed to investigate the fluidization characteristics of particulate systems. This X-ray CAT technique could have rather high spatial resolution (1%), while its temporal resolution is low, which does not allow the investigation of the dynamic bubble flow. The X-ray fluoroscopy technique has been applied to measure the bubble properties in the gas–solid fluidized bed. The X-ray fluoroscopy provides a high spatial resolution (0.1×0.1-mm pixel) and a relatively high temporal resolution of 30 Hz. Lately, the fast-scanning X-ray CAT system is applied to investigate the bubble shape and bubble structure in a fluidized catalyst bed.

The γ-ray density gauge technique has been applied to study the bubble size, frequency, and coalescence in the fluidized beds. The voidage between the radiation source and detector in the bed can be obtained by relating the ionization of gas to the amount of radiation received by the detector. The interpretation of the image obtained by the γ-ray density gauge is based on the penetration of γ-ray beam through the column and has the similar problem to X-ray technique. Since the depth resolution of this technique is not as accurate, the γ-ray tomography technique is often used to investigate particular cases, eg, the jet and bubble behavior above the distributor of a gas–solid fluidized bed. The γ-ray tomography system includes a γ-ray source and a NaI detector, which rotate along the axis of the measuring domain. The total scan time was up to 7.5 h. Like for X-ray, the γ-ray CAT is also developed to investigate the shape and penetration of the jets through the orifice of the distributor. The γ-ray CAT has a higher spatial resolution of 1.0×1.0-mm pixel and a reduced scan time of 3–4 h. This is a significant improvement compared to the earlier γ-ray tomography technique. Due to the slow rate of scanning, the γ-ray tomography technique can only be used to study the time-averaged properties of the flow system. It is not suitable for measuring the hydrodynamics of the highly fluctuating multiphase flow systems.

The ECT technique was used to study the dynamic flow behavior in multiphase flows of dielectric fluids and solids. The ECT technique has relatively low spatial resolution, but high temporal resolution, which is suitable for the quantitative study of the dynamic bubble flow behavior in the fluidized beds. By assuming the voidage is proportional to the measured permittivity, the ECT technique can measure the bubble size, rise velocity, and coalescence in the fluidized beds. The bubble formation at the distributor of a fluidized bed can also be studied by using the ECT with a quantitative filtered linear back projection reconstruction technique. For the system with an eight-electrode sensor plane mounted outside of the column wall, the cross-sectional area of each pixel is (3–5% of the column diameter)^2 and the temporal resolution is up to 210 Hz. The neural network multi-criteria optimization image reconstruction technique (NN–MOIRT) is coupled with the ECT to further enhance image reconstruction process. Recently, the Electrical Capacitance Volume Tomography (ECVT)

technique has been developed to study the 3D behavior of multiphase flows. The spatial resolution of the ECVT technique is (3–5% of the column diameter)[3] and the temporal resolution is 80 Hz, which is sufficient enough to provide useful information regarding the bubble formation and bubble dynamics in the gas–solid flow systems.

The MRI technique, which has been widely used in medical applications, is also applied for the measurement of multiphase flow systems, eg, the fixed and trickle beds. Particularly, the ultrafast MRI technique was developed to investigate the hydrodynamics in the trickle-bed reactors. However, the relatively high cost of the technique and rigorous fluid property requirements may hamper widespread usage of the MRI as a tomography technique for industrial processes.

Some other nonintrusive techniques are used for tracking the particle movement, and/or mapping the instantaneous or time-averaged, local, or cross-sectional averaged, phase hold-ups and phase velocities. They include PET, RPT, ultrasonic tomography, and Electrical Impedance Tomography (EIT).

Laser Techniques.   Nonintrusive laser techniques including the particle image velocimetry (PIV), phase Doppler anemometry (PDA), and laser Doppler velocimetry (LDV) are also widely used to study multiphase flow systems. Traditionally, these techniques have been used for gas–liquid systems, but now their applications are extended to the multiphase systems containing particles. The bubble characteristics in a slurry bubble column have been investigated using the 2D and 3D PIV techniques. The gas disengagement technique coupled with the PIV technique is used to investigate the effect of the solids loading on the bubble size distribution in both the bubble column and slurry bubble column. During the PIV measurements, fluorescent trace particles can be used for better identification between the different frames while directly measuring the interstitial velocity field variation in a porous medium (eg, fixed bed). The PDA technique is also used to measure the size, velocity, and holdup of solid and bubble phases in the three-phase fluidized beds. The turbulence energy distribution in bubble columns and three-phase fluidized beds can be investigated using the LDV technique by measuring the liquid velocity. For all the laser techniques, the laser beam needs to penetrate the flow system. Thus, the application of the laser techniques are limited only to the low gas holdup conditions.
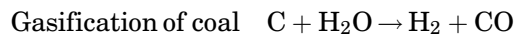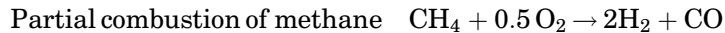

8. Industrial Applications

Particles and fluid–particle systems play important roles in the variety of industries including energy, environmental, pharmaceutical, chemical, petrochemical, bioprocessing, food processing, mining, mineral processing, and advanced materials. The detailed list of processes that use fluid–particle systems include coal combustion, water treatment, fermentation, agriculture, environmental cleanup, nuclear power generation, and the productions of industrial carbon, ceramic, potassium, paints, explosives, propellants, pulp, paper, synthetic fibers, petrochemicals, glass, sugar, starch, plastics, rubber, and pharmaceuticals. Successful application of these processes lies in comprehensive understanding of particle science and technology that provides important information for the characterization, formation, handling, processing, and utilization of a wide array of particles.

Many of the powder handling equipments and processing units described earlier are common in different applications. For example, pneumatic conveying of particulates is commonly used in pharmaceutical, food, coal, and mineral powder processing. Solid materials that are frequently transported via pneumatic conveying include flour, granular chemicals, lime, soda ash, plastic chips, coal, gunpowder pellets, ores, and grains. Granular materials in the food, pharmaceutical, chemical, and fuel industries are routinely processed through hoppers and standpipes. In chemical processes, spraying is often used to control and maximize the contract between the liquid droplet and the particle surface. The same technique is used to sugar coat cereals, chocolate, and other food products in the food industry, as well as to produce pills with sustained release coatings, moisture barriers, and cosmetic coats in the pharmaceutical industry. Thus, the common particle formation and processing mechanisms can be applied to processes that produce different products. In what follows, examples of particle and fluid–particle systems related to each industry are presented.

8.1. Energy.   High operating gas and/or liquid velocities for lean-phase fluidization yield a short contact time between the fluid and solid phases, which is desirable for process applications involving rapid chemical reactions. Gas–solid fluidization systems have been widely used in the utility industry (eg, in pulverized coal combustion, solid-waste incineration, rocket propellant combustion, and coal gasification). Another commercial application of the fluidization systems related to energy industry is Fischer–Tropsch (F–T) synthesis. The F–T synthesis is one of the most important, and perhaps the most and longest studied, application of three-phase fluidized systems is that concerning the hydrogenation of carbon monoxide in the liquid phase. The processes converting natural gas and coal to synthetic liquid fuels are called Gas-to-Liquid (GTL) and Coal-to-Liquid (CTL) technologies, respectively. The F–T synthesis forms saturated and unsaturated hydrocarbon compounds ranging from methane to high melting paraffin waxes and its chemical reaction is

$$(2n + 1)\mathrm{H}_2 + n\mathrm{CO} \rightarrow \mathrm{C}_n\mathrm{H}_{2n+2} + n\mathrm{H}_2\mathrm{O}$$
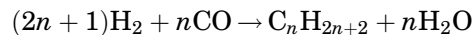
The syngas containing the building blocks, CO and H_2, for the F–T process can be produced by the partial combustion of methane (GTL case) or by the gasification of coal (CTL case).

$$\text{Partial combustion of methane} \quad \mathrm{CH}_4 + 0.5\,\mathrm{O}_2 \rightarrow 2\mathrm{H}_2 + \mathrm{CO}$$
$$\text{Gasification of coal} \quad \mathrm{C} + \mathrm{H}_2\mathrm{O} \rightarrow \mathrm{H}_2 + \mathrm{CO}$$

Selectivity to desired products including light hydrocarbons, gasoline, or diesel fuel depends on the catalyst employed, the reactor temperature and pressure, and type of process employed. By-products formed on a lesser scale include alcohols, ketones, acids, esters, and aromatics. The F–T synthesis combined with gasification technology has recently gained a great deal of attention due to its capability of converting a variety of feedstocks (eg, natural gas, coal, and biomass) to nonpetroleum-base liquid fuels. A new generation of F–T processes is being developed by incorporating various environmental control technologies for

sulfur, trace heavy metals, and carbon capture. Another energy-related application of particulate flows is the utilization of graphite suspension flows in nuclear reactor cooling and solar energy transport.

8.2. Chemical and Petrochemical.   Particle technology also influences chemical industries a great deal since most of the reactants and products are in particulate form. The development of any chemical process involves the formulation of catalyst particles and catalyst support based on desired particle characterizations (eg, high surface area and thermal stability). A process that allows controlled contact between reactants is then developed based on the system requirement (eg, reaction kinetics and heat and mass transfer). The subsequent separation of reaction products also involves fluid–particle interaction.

One of the common types of fluid–particle reactor systems is a fluidized bed reactor. Fluidization systems have been widely used in the petrochemical industry (eg, in FCC). Heavy oil, petroleum resid, and synthetic crude are all commercially processed in three-phase fluidized beds. Resid processing technology has recently grown in importance since large quantity of world oil reserves consist of heavy crude and bitumen. During hydrotreating processes, the feedstock is upgraded by reacting with hydrogen over a bed of catalysts. The hydrotreating units are commonly referred to in industry as an "ebullated bed" where particles are in "ebullation" included by gas–liquid phases. Maleic anhydride is also produced in a fluidized bed reactor from n-butane and its chemical reaction is as follows.

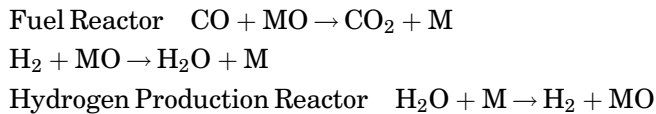$$CH_3CH_2CH_2CH_3 + 3.5\,O_2 \rightarrow C_2H_2(CO)_2O + 4H_2O$$
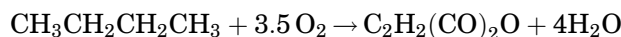
Other chemical applications of particulate systems include electrodes, granulation, adiponitrile production, calcium bisulfite acid production, sand filter cleaning, crystallization, flotation, polymerization, methanation, and methanol synthesis.

8.3. Environmental.   The design and operation of the most industrial environmental control processes also involve particulate flows. For example, a fluidized bed has been extensively used for biological wastewater treatment since it provides maximum surface area of contact. In such a device, organic or inorganic pollutants in wastewater are removed by microbes immobilized on the surface of fluidized particles. The particles coated with biofilm are referred as bioparticles. Other types of bioreactors for wastewater treatment include activated sludge aeration tanks, trickling filters, rotating biological contactors, and submerged filters. These systems also often involve fluid–particle systems.

Another important environmental application of particulate flows is air pollution control. Both sulfur dioxide, trace heavy metals, and fine particulates (eg, ash) are commonly found in flue gas of processes, eg, heavy oil and coal combustion, smelting operations, sulfuric acid manufacture, and metallurgical processes. Consequently, sulfur dioxide, trace heavy metals and particulate removal are of considerable environmental importance. Wet scrubbers provide a relatively simple, yet efficient, method of removal of sulfur dioxide, while the injection calcium-base sorbent into a hot furnace provides a less energy intensive method of sulfur control. Cyclones, electrostatic precipitators, gravity settling,

and filtration operations are all used to capture particulates from the various fluid–particle flows.

Currently, there are significant research efforts to intensify the chemical processes by developing a process that can simultaneously produce intended chemicals while capturing air pollutants. A great example is chemical looping technology that converts syngas or coal into hydrogen while generating sequestration-ready carbon dioxide stream. Carbon dioxide is one of the greenhouse gases that contribute to global warming. The chemical looping process allows production of clean, carbon-free fuel (hydrogen) while eliminating highly energy intensive carbon capture process, eg, amine scrubbing. As shown in the following chemical equations, two separate reactors are used for the chemical looping process and the produced gases (eg, H_2 and CO_2) are not mixed, since metal oxide particles are used as oxygen carrier between two reactors.

$$\text{Fuel Reactor} \quad CO + MO \rightarrow CO_2 + M$$
$$H_2 + MO \rightarrow H_2O + M$$
$$\text{Hydrogen Production Reactor} \quad H_2O + M \rightarrow H_2 + MO$$

where M is metal and MO is metal oxide. The future success of the chemical looping technology lies in the development of the smart particles and the efficient particle handling throughout the process.

8.4. Bioprocessing and Food Processing. A bioprocess refers to physical and chemical transformations of living cells or their components (eg, bacteria and enzymes). Immobilized cell systems refer to suspended plant cells, mammalian cells (eg, hybridoma), or flocculated microbial cells of size >10 μm as being heterogeneous to the liquid phase. Although the physical and chemical properties of the living cells could be somewhat different from those of the common chemical reactants, similar particle handling and processing fundamentals can be applied in designing such bioreactor systems.

Particulate systems, eg, three-phase fluidized-bed bioreactors, were used in various bioprocesses, eg, the production of ethanol, antibiotics, glutathione, and enzymes, including α-amylase and alkaline proteinase. The pertinent operational considerations essential to the successful application of multiphase bioreactors include cell immobilization, substrate diffusivities, optimal design consideration, and economics. Fluidized-bed reactors and hollow fiber reactors offer some unique advantages for biological processing using immobilized cells. Particularly, three-phase fluidized-bed bioreactors provides good mixing of solid and liquid phases, high gas–liquid and liquid–solid mass transfer, easy rejuvenation of biocatalyst, and low attrition of biocatalyst. In a three-phase fluidized-bed fermentor or bioreactor, the solid phase comprises immobilized cell (or enzyme) particles in which the desired biochemical reactions occur. The culture medium necessary for cell growth and maintenance constitutes the liquid phase. The constituents of the gas phase depend on whether the fermentation process is aerobic or anaerobic. For aerobic fermentation, air or oxygen used for microbial respiration and/or CO_2 evolved from metabolism constitute the gas phase. For anaerobic fermentation, an inert gas, eg, nitrogen, or gases

produced during fermentation (eg, CO_2 and H_2) constitute the gas phase and provide solids mixing.

Food processing is frequently related to bioprocessing and deals with various agricultural processes. The quantity of various food items that are currently being produced in massive commercial scales are tremendous ranging from packaged eggs to frozen dinners. Food products are in the forms of various stages of processing (eg, flour vs. bread). Often, its processing machineries are similar to those used in chemical processes. The development of different food processing systems focuses on the design of equipment and processes to produce foods, the implementation of preservation methods, and the advancement in food packaging technology. Quality control and safety during food production are the most important aspects in food processing. Recently, biotechnology has been applied to food processing to produce food products with specific functions (eg, low fat yogurt) containing a live bacteria (eg, bifidus regularis) to help regulate the digestive system.

8.5. Pharmaceutical. A relatively new and challenging area that applies to particle technology is the pharmaceutical industry. Many of the pharmaceutical products are in powder or pellet forms, and hence, particle technology plays an essential role in designing, operating, and improving pharmaceutical processes. Particularly, purification and mixing of the fine powders are very important factors in pharmaceutical processing in order to maintain the quality of the products (eg, potency of each pill). Currently, a number of areas of science and technology (eg, cell biology, protein engineering, neuroengineering, biosensors, tissue engineering, biocompatible materials, biopharmaceuticals, drug delivery, and nanotechnology) are coupled to develop a wide array of innovative ways of producing and applying various medicines.

Antibiotics account for a major portion of industrial biotechnological production. A variety of particle processing and reactor systems are used to produce commercially available pharmaceutical products. For example, three-phase fluidized beds that are used for the bioproduction of ethanol can also be used for the production of antibiotics as well as amino acids and enzymes (2). The same principles are applied for the design of such reactors, while the operating conditions, eg, the reactor temperature and residence time, can be varied. Other examples of pharmaceutical processes include production of L-isoleucine, penicillin, bacitracin, and patulin (2). Industrial production of antibiotics is mostly limited to the use of free suspended cell systems. However, considerable merit exists for use of the immobilized cell system for antibiotics, as evidenced in patulin, penicillin, and bacitracin production.

Another area within the pharmaceutical industry that is heavily involved with particle technology is drug delivery. As the science of medicine advances, the way that medicine is applied to patients has changed accordingly. For example, diabetic patients have traditionally administrated insulin via painful needle injection. In order to improve the patients' well being, alternative ways of injecting insulin are being investigated: (1) insulin patch using transdermal transport through the skin, (2) powder insulin to be inhaled, and (3) buccal insulin in a spray form. For the success of these drug delivery methods, a meticulous formation of engineered insulin particles is required. For example, the size and density of insulin particles or buccal insulin droplets have to be well controlled so

that they can be easily inhaled into the lung and also adhere to the surface once they arrive at the lung. A patch system of drug delivery is already widely used for various medicines including birth control and nicotine control. As witnessed from these examples, particle technology will continue to play an important role in the pharmaceutical industry. Particularly, with the recent development of nanotechnology, the applications of engineered particles in biomedical research, disease diagnosis, and even therapy become limitless (13).

8.6. Minerals Mining and Processing. One of the traditional industrial applications of particles and fluid–particle systems is minerals mining and processing. Mining refers to the extraction of geological materials from the earth. In a broad sense, mining can also include procurement of natural gas, petroleum, and ground water. Coal is globally mined in vast quantities, and copper, iron, lead, nickel, tin, and uranium are also mined for various industrial applications. Other materials being mined include limestone, phosphate, oil shales, and rock salts. Precious materials, eg, gold, silver, diamonds, and gem stones are also mined. Once they are mined, ores are processed by crushing and grinding, and classified into different particle sizes. Due to its heterogeneous nature of mineral ores, after comminution process mineral particles are chemically treated to liberate and concentrate the specific components of values based on their physical and chemical properties. Hydrometallurgical or pyrometallurgical processes are generally used to treat minerals. The processed minerals or chemicals extracted from the minerals are used in a variety of industries ranging from paving roads using aggregates to copper wiring in microdevices.

8.7. Advanced Materials. In addition to particulate materials involved in the above mentioned industries, a variety of new generation materials (eg, ceramics, polymers, magnetic and electronic materials), and biomedical materials, (eg, implants) are synthesized and utilized in a number of different fields. Particularly, with the recent emphasis on nanotechnology and biotechnology novel materials and innovative synthesis techniques are being developed to accommodate newly invented industrial needs. Carbon nanotubes–nanofibers, which possess astonishing mechanical strength, high thermal conductivity, and unique electrical properties, are one of the examples. The application of carbon nanotubes includes the modification of the properties of the existing materials, eg, polymers. Inorganic nanotubes have also been synthesized in similar processes.

Another type of materials being produced based on particle technology is energetic material, compounds that rapidly decompose without the presence of oxygen. They include propellants, explosives, pyrotechnics, initiating substances, and thermally unstable substances. Particulate energetic materials are manufactured by various methods involving size reduction, crystallization, atomization, particle formation using supercritical fluids and microencapsulation. A new sol–gel technique is also being investigated to safely produce nanocomposite energetic materials with better performance.

Semiconductor refers to a solid having controllable electrical conductivity over a wide range, either permanently or dynamically. Semiconductors, eg, silicon, have gained immense technological and economical importance with the development of the modern electrical devices ranging from cellular phones to super computers.

9. Hazards

There are a number of industrial, environmental, and health hazards related to the processing and handling of particles and powders. One of the common industrial hazards is dust explosions that often occur in grain silos and flour mills. The damage caused by dust explosion can be even greater when particles or powders dispersed in air are combustible (eg, coal). The accumulation of electrostatic charges is generally suspected as the main cause of dust explosion. Electrostatic charge buildup due to contact electrification can also lead to particle agglomeration causing undesirable sheet formation in polymer reactors. Moreover, accumulated static charges can instigate a spark or corona discharge yielding reactor explosions. The particle size distribution and moisture content are known to affect dust explosion and other static charge related phenomena, but the actual mechanisms resulting electrostatic charge accumulation and hazardous electrical discharge are complex. Several methods including grounding, coating inner-reactor walls, increasing humidity, and adding fine particles or antistatic agents have been suggested to control static problems in chemical processes. However, their effectiveness is rather limited and these methods often cannot be applied to many of the processes since adding humidity or antistatic agents can be poisonous to the reactive systems. There are a number of ongoing research efforts to improve the online electrostatic detection systems and to develop an efficient charge elimination technology, but they are still in their development stage. Hence, particles should be handled with great care when they are exposed to heat and high velocity in processes, eg, pneumatic conveying, spray drying, milling, and fluidization.

The other major hazardous characteristic of industrial powder comes from its size. People who work in powder handling or processing industries are often exposed to health hazard related to inhaling and contacting fine particles. Particles <10 μm can easily be dispersed into environment even under gentle movement of surrounding fluid (eg, air). Once they are suspended, they do not settle quickly and cause irritation to the eyes and lungs of people who work within that area. If the dispersed particles are corrosive, reactive, toxic, radioactive, or biologically active, the health hazard is dramatically increased. The shape of the particles can also contribute to health hazards. Some fibrous substances (ie, asbestos) are also known to be dangerous to humans due to their needle-like shape. Asbestos and related minerals of the serpentine groups, eg, chrysotiles, are naturally occurring minerals that possess fibers. In their natural state, they are generally safe to handle. However, breathing fibrous dust of these materials may pose a health hazard, eg, lung cancer. It is strongly recommended that protective gloves and a filter mask be worn while handling fine or fibrous materials.

With fast growing interests and new applications of nanoparticles, a new set of health and environmental hazards related to handling and processing of nanoparticles have also emerged. Nanoparticles are attractive in many industrial processes since they have exceptionally high surface area per unit volume or weight making them very reactive or catalytic (5). Although the effects of highly reactive nanoparticles on human health are still unknown, the efforts

to minimize human and environmental exposure to these nanoparticles during handling and processing continue.

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Table 1.   **Examples of Applications of Particulate Systems**

Types of applications	Examples
physical processing	powder flow, blending, separation, coating, and pelletizing urea granulation and drying dust/particulate collection and removal
chemical, petrochemical, metallurgical, and mineral processing	solid oxide fuel cell fluid catalytic cracking coal combustion, gasification, and liquefaction fischer–tropsch synthesis of liquid fuels uranium processing pryolysis of oil shale production of polyethylene and polyolefins
biochemical, pharmaceutical, and food processing	ethanol production from biomass as a renewable energy source treatment of municipal sewage wastewater drug formulation for delivery via pulmonary inhalation calcium phosphate biomaterials used in clinical medicine patuline production by penicillium urticae freeze-dried ice cream
advanced materials	chemical mechanical planarization for semiconductor industry electronic ink—printed circuits inks containing metallic colloidal particles in organic solvent synthesis of rugged nanophosphors for leds and diagnostics
other applications	nanoparticle synthesis (eg, carbon nanotube, mixed-metal oxide catalysts, nanocomposites, and quantum dots) photonic crystal-based optical devices emulsion templating

Table 2. **Size Definitions of Nonspherical Particles**

Size	Definition
sieve diameter	width of the minimum square aperture through which the particle will pass
martin's diameter	averaged cord length of a particle that equally divides the projected area
feret's diameter	averaged distance between pairs of parallel tangents to the projected outline of the particle
projected area diameter	diameter of a sphere having the same projected area as the particle
surface diameter	diameter of a sphere having the same surface area as the particle
volume diameter	diameter of a sphere having the same volume as the particle
sauter's diameter	diameter of a sphere having the same ratio of external surface to volume as the particle
dynamic diameter	diameter of a sphere having the same density and the same terminal velocity as the particle in a fluid of the same density and viscosity
scattering diameter	diameter of a sphere having the same scattering characteristics (eg, mie-scattering or doppler shift) as the particle

Table 3.   **List of Typical Particle Sizing Methods and Their Sizing Range**

Method		Size range, μm
sieving	woven wire	37–5660
	electroformed	5–120
	punched plate	50–125,000
microscopy	optical	0.8–150
	electron	0.001–5
sedimentation	gravitational	5–100
	centrifugal	0.001–1,000
Fraunhofer diffraction		0.1–1,000
doppler phase shift		1–10,000

Table 4.   **Definitions of Particle Shape**

|	
spherical	smooth global shape
acicular	slender and pointed, needle-like
angular	sharp-edged or having roughly polyhedral shape
crystalline	geometric shape, regularly ordered, repeating pattern
dendritic	branched crystalline shape
fibrous	regularly or irregularly thread-like or elongated shape
flaky	plate-like layered structure
granular	approximately equidimensional shape
irregular	shape without any symmetry
modular	rounded, irregular shape
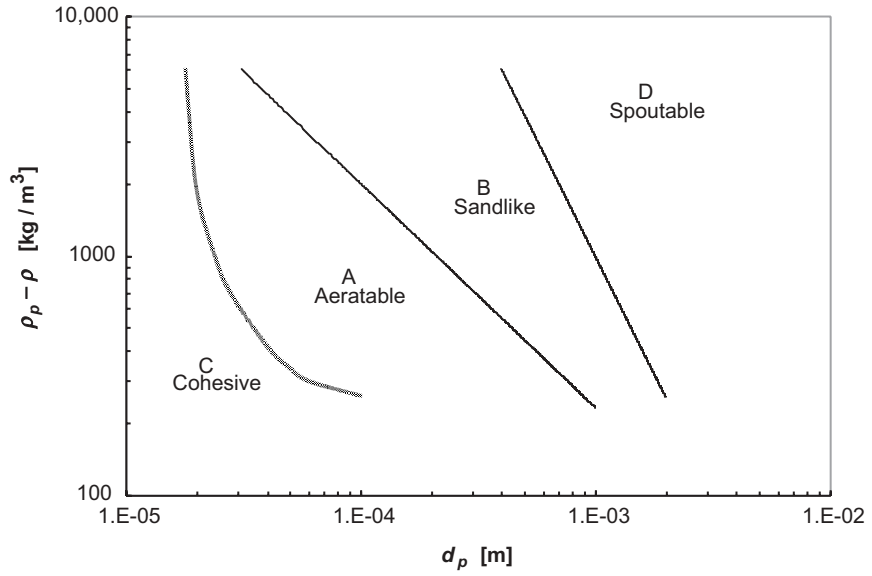
Fig. 1. Geldart's classification of fluidized particles.