Hydrodynamics

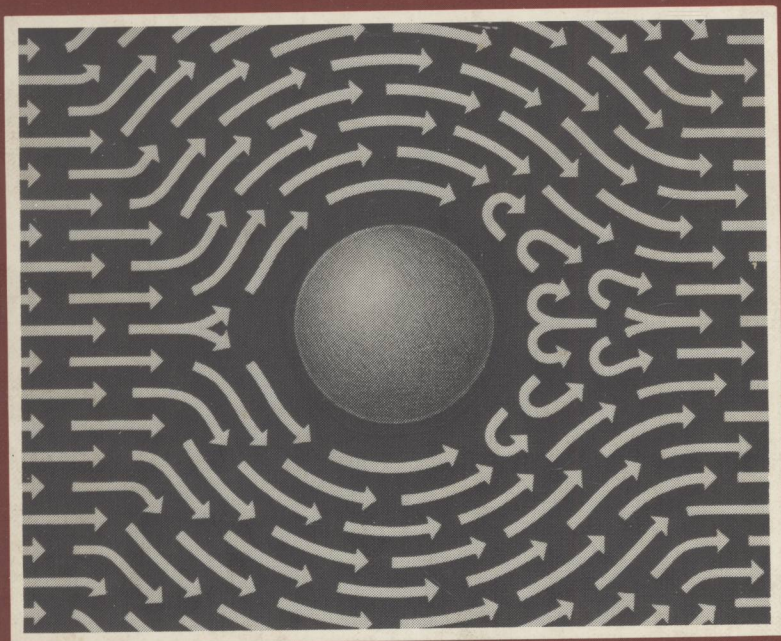## of

Gas-Solids
Fluidization

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Hydrodynamics of Gas-Solids Fluidization

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PREFACE

Gas-solid fluidization is a subject having wide engineering applications overlapping different industries. Fluidized-solids technology has grown almost exponentially over the past several decades with commercial applications in the production of vinyl chloride, phthalic anhydride, melamine, polyethylene, polypropylene, and fluidized catalytic cracking of petroleum. Fluidization is essentially a low-energy method of contacting granular solids with process fluids, and as such, could be used in the production of clean, inexpensive energy from coal resources. In the development of the synthetic fuels industry, fluidized reactor systems are being considered for coal gasification, coal liquefaction, and shale pyrolysis. Other present-day applications include combustion, nuclear fuel preparation, and operations in drying, coating, and similar physical methods of manufacturing.

Despite the large-scale applications of this technology, fluidization remains a comparatively less-developed area of chemical engineering. Scale-up to commercial systems is often a formidable task, requiring costly pilot-plant testing in successively larger units or operations. The design literature in general is poorly organized and in some cases contradictory, particularly where heat and mass exchanges and/or chemical reactions are involved. Part of this dilemma lies in the inadequate understanding of the hydrodynamic phenomena in systems involving gas-solids flows. Understanding the complex interaction between particles, and particles and fluid is critical not only to the design of reactor systems but to their peripheral operations, which include solids transfer lines, risers, product/recycle separation schemes, feedstock and catalyst feeding systems, etc.

It is the intent of this book to relate hydrodynamic concepts of gas-solid flows to design practices in fluidization engineering. Many of the early chapters deal with the properties and characteristics of fluid-particle transport and contacting. These fundamental discussions are applied in subsequent chapters to industrial problems.

Finally, this volume contains two contributed chapters prepared by experts. We wish to acknowledge each of these contributors. Without the efforts of these individuals, this volume would not have been possible.

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Properties and Characteristics of Loose Solids

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INTRODUCTION

Many granular and powdered forms of solids are produced in manufacturing processes as either final products or intermediate constituents for producing marketable items. These materials are almost never uniform in size and are often highly irregular in shape-characteristics which largely establish their hydrodynamic behavior in both bulk form and in two-phase systems. These materials are produced by crushing, grinding, precipitation, attrition, spraying, or other particulate-forming processes, and only under very carefully controlled conditions do they appear in relatively uniform sizes and shapes. The quantitative correlation of bulk particulate behavior, both alone and in fluid-solid systems is difficult because of the large number of parameters that relate to particle size and size distribution, particle shape, particle surface characteristics, and discrete particle physical properties. The conventional characterization of granular and powdered materials is in terms of an appropriately defined mean size. Regardless of the measurement method employed to define a size distribution, data can be redefined in terms of an appropriate characteristic dimension or size, which most often is an equivalent spherical particle diameter. This has the distinct advantage of allowing granular solid properties to be related through standard hydrodynamic correlations when dealing with two-phase flow systems.

This first chapter introduces some basic definitions and physical and aerodynamic properties of discrete solids. Subsequent chapters apply these concepts to describing the two-phase phenomenon and in extending analogies to engineering calculations.

PHYSICAL PROPERTIES OF LOOSE MATERIALS

Loose solid matter is composed of an assemblage of large numbers of individual particulates. The physical properties and forces of attraction which exist between individual particles have important effects on their flow behavior when subjected to fluidization by gas or liquid media. With many materials, forces of attraction exist between particles, in which case the material is described as being cohesive. Ideal loose solids have no forces of attraction between them. The properties of loose materials in contrast to fluids and composite solids are characterized by several parameters that must be measured or known prior to the design of any fluid-solids contacting system.

The first of these important properties is the density of the material, of which there are several specific terms, namely, bulk, particle and skeletal densities.

The *bulk density* of solids is the overall density of the loose material including the interparticle distance of separation. It is defined as the overall mass of the material per unit volume. A material's bulk density is sensitive to the particle size, the mean particle density, moisture content, and the interparticle separation (i.e., degree of solids packing). It is measured simply by pouring a weighed sample of particles through a funnel into a graduated cylinder, and from this the volume occupied de-

termines the loose bulk density. By gently vibrating the container walls, the distance between particles decreases and hence, the volume decreases. The material thus becomes denser with time and its bulk density achieves some limiting value, ϱ_{max}, known as the *tapped* or *packed bulk density.*

The ratio of $\varrho_{max}/\varrho_{min}$ can be as high as 1.52 depending on the material. Consequently, when bulk densities are reported it is important to note whether the value was determined under loose or tapped conditions, along with the mean particle size. Most literature values report an average bulk density that is representative of the material most often handled. Loose solids may be broadly characterized according to their bulk densities:

Light material	$\varrho_b < 600$ kg/m^3
Average	$600 < \varrho_b < 2,000$ kg/m^3
Extra heavy	$\varrho_b > 2,000$ kg/m^3

The loose bulk density (kg/m^3) can be computed as:

$$\varrho_b = \frac{G_1 - G}{V} \tag{1-1}$$

where G_1, G = weights of filled and empty cylinders
V = internal volume of cylinder

Bulk density is related to particle density through the interparticle void fraction ϵ in the sample.

$$\varrho_b = \varrho_p(1 - \epsilon) \tag{1-2}$$

The value of ϵ varies between the limits of 0 and unity; however, many particles of interest in fluidization have a loosely poured voidage of approximately 0.4 to 0.45.

Particle density, ϱ_p, is the density of a particle including the pores or voids within the individual solids. It is defined as the weight of the particle divided by the volume occupied by the entire particle. Some textbooks refer to particle density as the material's *apparent density.*

The *skeletal density,* ϱ_s, also called the *true density,* is defined as the density of a single particle excluding the pores. That is, it is the density of the *skeleton* of the particle if the particle is porous. For nonporous materials, skeletal and particle densities are equivalent. For porous particles, skeletal densities are higher than the particle density.

Measurements of the skeletal density are made by liquid or gas pycnometers. When liquids are used, the pycnometer has a fixed and known volume. A specified weight of solids is immersed in a liquid of known density, which wets the solids and penetrates into the pores of the particles. The volume of liquid displaced by the solids is then determined by difference and the skeletal density of the weighed solids computed from the measured displaced volume. The most common liquid used in pycnometer work is water. For materials whose specific gravities are less than water (e.g., coal and coke particles), Varsol is used.

Gas pycnometers provide more accurate measurements of the skeletal density due to better penetration of the particle pores by the gas. They are, however, less frequently employed because of cost and elaborate procedures required during measurements.

The particle and skeletal densities are related through the following equation:

$$\varrho_p = \frac{1 + \varrho_f \xi}{\dfrac{1}{\varrho_s} + \xi} \tag{1-3}$$

where ϱ_p = particle density
   ϱ_s = skeletal density
   ϱ_f = density of fluid contained in pores of solid
   ξ = pore volume per unit of mass of solids

When the particle pores are saturated with gas, $\xi \varrho_f$ is negligible, and Equation 1-3 reduces to:

$$\frac{1}{\varrho_p} = \frac{1}{\varrho_s} + \xi \tag{1-4}$$

Direct measurement of particle density can be made by immersing the material in a non-wetting fluid, such as mercury, which does not penetrate into the pores. The technique resembles that of the liquid pycnometer with the exception that the volume of fluid displaced is that for the entire particle and not just the skeleton.

Another property of importance is the *pore volume*. It can be measured indirectly from the adsorption and/or desorption isotherms of equilibrium quantities of gas absorbed or desorbed over a range of relative pressures. Pore volume can also be measured by mercury intrusion techniques, whereby a hydrostatic pressure is used to force mercury into the pores to generate a plot of penetration volume versus pressure. Since the size of the pore openings is related to the pressure, mercury intrusion techniques provide information on the pore size distribution and the total pore volume.

Moisture can significantly affect loose materials, particularly their flowability. Low temperatures, particle bridging, and caking can alter interparticle void fractions and cause dramatic changes in bulk density. Moisture becomes bound to solids because of mechanical, physicochemical, and chemical mechanisms. Moisture retained between particles and on their surfaces is strictly a mechanical mechanism. Physicochemical binding results when moisture penetrates inside particle pores because of diffusion and adsorption onto pore walls. Chemically bound moisture appears as hydrated or crystalline structures. The terms *moisture* or *moisture content* is used to denote the degree of liquid retained on and in solids.

Moisture is defined as the ratio of the fluid's weight retained by solids to the weight of wet material:

$$W = \frac{G_w - G_d}{G_w} \tag{1-5}$$

where G_w and G_d are the weights of wet and absolute dry material, respectively. Moisture content, W_c, is the ratio of the moisture weight to the weight of absolute dry material:

$$W_c = \frac{G_w - G_d}{G_d} \tag{1-6}$$

Values of W and W_c can be expressed as either fractions or percents. The presence of moisture tends to increase the relationship between moisture content and the density of loose or lump materials as follows:

$$\varrho_m = \varrho(1 + W_c) \tag{1-7}$$

And for dusty and powdered materials:

$$\varrho_m = \varrho \frac{1 + W_c}{(1 + \dfrac{W_c}{3}\varrho_f/\varrho_p)} \tag{1-8}$$

where ϱ_m, ϱ = densities of wet and dry loose materials, respectively
ϱ_p = particle density
ϱ_f = density of liquid filling the solid particle pores

In addition to the physical properties just described there are those properties which affect the flowability of the material. Specifically, these properties are the material's angle of repose, angle of internal friction, and the angle of slide.

ANGLES OF REPOSE, INTERNAL FRICTION, AND SLIDE

The *angle of repose* is defined as the angle between a line of repose of loose material and a horizontal plane. Its value depends on the magnitude of friction and adhesion between particles and determines the mobility of loose solids, which is a critical parameter in designing conical discharge and feeding nozzles and in establishing vessel geometries. In all cases the slopes of such nozzles should exceed the angle of repose.

The angle of repose is the measured angle between a horizontal plane and the top of a pile of solids. The *poured angle* of repose is obtained when a pile of solids is formed, whereas the *drained angle* results when solids are drained from a bin. Figure 1-1 distinguishes between the two terms signifying the angle of repose. For monosized particles or particles with a relatively narrow size distribution, the

drained and poured angles are approximately the same. If, however, the solids have a wide size distribution, the drained angle is higher than the poured angle.

In bin design, the drained angle is more important. However, the differences between the angles are rarely important, and since the poured angle is easier to measure, it is most frequently reported in the literature. In general, the lower the angle of repose is, the more free flowing is the material, and hence, the shallower the bin angle required. Materials can be roughly categorized according to their angles of repose as follows:

- For very free-flowing granules: $25° < \beta < 30°$
- For free-flowing granules: $30° < \beta < 38°$
- For fair to passable flow of powders: $38° < \beta < 45°$
- For cohesive powders: $45° < \beta < 55°$
- For very cohesive powders: $55° < \beta < 70°$

The angle of repose is sensitive to the conditions of the supporting surface—the smoother the surface, the smaller the angle. The angle may also be reduced by vibrating the supporting surface. When handling slow moving materials having large angles of repose, well-designed bunkers and hoppers are provided with highly polished internal surfaces and low amplitude vibrators.

The angle is also sensitive to moisture. Specifically, moisture tends to increase the angle of repose. The variation of β with moisture content is likely due to the surface layer of moisture that surrounds each particle and surface tension effects which bind aggregates of solids together.

The *angle of internal friction, α,* is defined as the equilibrium angle between flowing particles and bulk or stationary solids in a bin. Figure 1-2 illustrates the definition. The angle of internal friction is invariably greater than the angle of repose.

The *angle of slide* is defined as the angle from the horizontal of an inclined surface on which an amount of material will slide downward due to the influence of
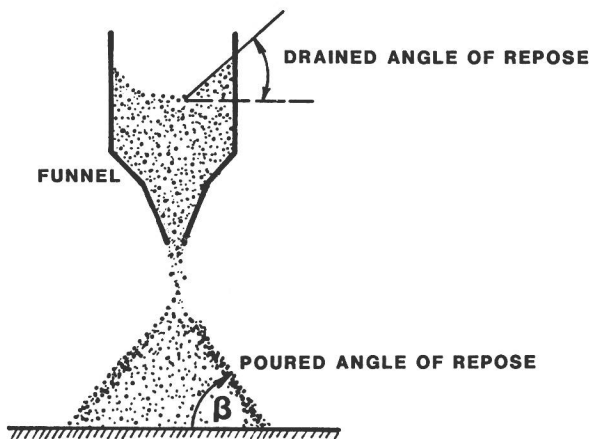
Figure 1-1. Illustration of the angle of repose for granular solids.

Figure 1-2. Illustration of the angle of intern *' friction.

Table 1-1
Physico-Mechanical Properties of Loose Materials

Loose Material	Bulk Density (g/cm³)	Angle of Repose (degrees)	Friction Coefficient	
			Inside	Outside on Steel
Sulfur	0.67	40	0.8	0.625
Magnesite-caustic	1.02	31	0.575	0.5
Magnesium oxide	0.47	36	0.49	0.37
Phosphate powder	1.52	29	0.52	0.48
Calcium chloride	0.68	35	0.63	0.58
Napthalene (crushed)	0.57	37	0.725	0.6
Anhydrous sodium carbonate	0.585	41	0.875	0.675
Sodium chloride (fine)	0.93	38	0.725	0.625
Carbamide (powdered)	0.54	42	0.825	0.56
Superphosphate (granulated)	1.1	31	0.64	0.46
(powdered)	0.8	36	0.71	0.7
Nitrophoska (granulated)	1.1	38	0.55	0.4
Salicylic acid (powdered)	0.46	44	0.95	0.78
Talc	0.85	40	—	—
Cement	1.15	30	0.5	0.45
Chalk	1.1	42	0.81	0.76
Sand (fine)	1.51	33	1.0	0.58
Graphite	0.45	40	—	—
Coal (fine)	0.95	36	0.67	0.47
Earth (dry)	1.2	30	0.9	0.57
Wheat	0.77	29	0.35	0.28
Peas	0.743	26	0.4	0.42

gravity. The angle is important in the design of chutes and hoppers as well as pneumatic conveying systems. It provides a measure of the relative adhesiveness of a dry material to a dissimilar surface. The angle depends on the type of solids, the physical and surface properties (e.g., roughness, cleanliness, dryness), the surface configuration (e.g., degree of curvature), the manner in which the solids are placed on the surface, and the rate of change of the slope of the surface during measurements. Table 1-1 provides typical values of loose solids as measured without vibration of the horizontal support surface.

FORCES OF ADHESION AND SOLIDS FLOWABILITY

The ability of solids to flow freely under the influence of gravity is called *fluidity* and is characterized by flow through an orifice. It is a function of the granulometric composition of the solids, the particle geometry and size distribution, the coefficient of internal friction, moisture content, and other parameters. A material's fluidity is important to the design of bins, bunkers, and a variety of feeding and mixing devices. Specific to these systems is its influence on requirement times for filling and discharge. Fluidity can be characterized in terms of a coefficient:

$$K_f = \tau' r^{2.58/G} \tag{1-9}$$

where K_f = fluidity coefficient
τ' = loose solids' discharge time through funnel (s)
r = orifice radius (mm)
G = total sample weight (gms)

The coefficient varies over a wide range depending on the material properties, with typical values being $1.2 \backsim 6.4$ for metal powders and $3 \backsim 4$ for quartz sand. In general, the larger K_f is, the more tightly packed are the solids.

The limiting outflow velocity through orifices in the bottoms of bins may be estimated from the following expression:

$$V_o = K_e F^{n'} \tag{1-10}$$

where F = cross-sectional area of orifice
K_e, n' = experimentally determined coefficients

For granular materials the following formula is recommended:

$$V_o = (2.546 - 0.162\bar{d}_p)F^{0.25} \tag{1-11}$$

where $\bar{d}_p$ is the mean particle diameter (mm) and F and V_o are in units of m² and m/s, respectively.

Equations 1-9 to 1-11 are empirical relations that describe solids flow behavior, but do not relate specific solid properties other than perhaps particle size. How properties affect solids flowability depends on the specific forces of attraction between particles. This can be described by the phenomena of adhesion and agglutination, as well as the mechanical properties of loose solids.

Adhesion

Adhesion is the phenomenon observed when particles stick to solid surfaces. Obviously, this is undesirable and must be accounted for in the design of bins, chutes,

pneumatic conveying systems, and gas-solid contacting devices. Adhesion is caused by molecular, capillary, electrical, and coulombic forces. Often, these forces interact, and it is difficult to distinguish which force is primarily responsible. There are however, exceptions where one force dominates.

The *molecular forces of adhesion* are determined by van der Waals' forces of interaction between particle molecules and the supporting surface. These forces are evident even before there is direct contact between the particles and surface, and they depend on the properties and size of the pair of contacting bodies, the roughness of the supporting surface, and the area of contact. Molecular adhesion forces may be reduced by polishing the supporting surface and by decreasing the solid's particle size.

Capillary forces of adhesion are due to the condensation of water vapor into the pores of loose solids during the presence of a wet film. A liquid memiscus develops between the particles and the supporting surface, resulting in the formation of surface forces. These forces press the solids onto the vessel surface. Capillary forces may be reduced by hydrophobing the surface (i.e., by making it moisture resistant through the addition of a liquid surface-active agent in the loose material).

Electrical forces of adhesion only manifest during direct contact between particles and the supporting surface. During mixing, particles rub against each other, as well as against the vessel walls and any internals. This action gives rise to electrical charges, causing a potential difference and resulting in particles sticking to each other. The greater the contact potential difference, the greater are the electrical adhesion forces. The contact potential difference depends on the amount of charge on the particles' surfaces and the supporting surface. When particles come into contact with a semi-conductor (e.g., metal paint, plastics) a contact potential difference develops that is much greater than that observed during contact with a conductor (metals). For this reason, particles will more readily adhere to painted surfaces than to pure metals.

Coulomb's forces of adhesion arise when charged particles approach the supporting surface. When this happens, on the opposite side of the surface, charges are generated that are equal to the particle charges but are of opposite sign. Such a case leads to mirror-image coulombic forces. These forces are only manifested by the presence of a gap between particles and the supporting surface. When a particle touches the supporting surface, the charges escape, resulting in a decrease of Coulomb's forces. The higher the wall's conductivity, the less pronounced are Coulomb's forces and consequently, the smaller the forces of adhesion. Surface wetness also promotes the process.

Each type of adhesion force has a different effect depending on particle size. In terms of particle radius, these relationships are as follows: Coulomb's forces are proportional to $1/r_p^2$; electrical forces, to $r_p^{0.666}$; molecular forces to r_p; capillary forces, $r_p(1 - r_p^{x-1})$, for exponent $x > 1$.

Because of the radically different natures of the adhesion component forces, a universal method for minimizing them is not possible. For example, while the hydrophobization of the support surface decreases capillary forces, it tends to increase electrical and coulombic forces; whereas increasing wetness decreases electrical and Coulomb's forces but increases capillary forces.