Chemical Engineering Division, ASEE
1999 Union Carbide Award Lecture

PARTICLE DYNAMICS IN FLUIDIZATION AND FLUID-PARTICLE SYSTEMS

*Part 1. Educational Issues**

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It is indeed a great honor for me to be the recipient of the 1999 ASEE Chemical Engineering Division's Union Carbide Lectureship Award. I am particularly honored to be included among the outstanding educators who have received this award in the past.

Particle technology is not well covered in the chemical engineering curriculum, but it is an important area for chemical engineers from both industrial and academic perspectives. In this lecture I will specifically discuss particle dynamics and will use fluidization and fluid-particle systems as examples to illustrate the importance to chemical engineers of knowing the particle dynamics of these systems.

I would like to define the scope of my lecture as follows:

1. *Observations on educational issues in particle dynamics.*
2. *Comparison of the mechanics of flow of solids and fluids.*
3. *Sample subjects of interdisciplinary nature.*
4. *Sample subjects of pertinence to chemical engineers.*
5. *Computational fluid dynamics of particulate systems.*

In Part 1, appearing here, I will discuss points 1 through 3. I will discuss points 4 and 5 in Part 2, which will be published in the next issue of *CEE.*

OBSERVATIONS ON EDUCATIONAL ISSUES IN PARTICLE DYNAMICS

One of the most important fluid-particle applications in the chemical and petrochemical industries is FCC (fluid catalytic cracking) systems.[1] In North America alone, there are 120 to 135 FCC units in operation, with each processing 40,000 to 50,000 barrels of gas oil per day to generate olefin gas, gasoline, diesel, and heavy cycle gas oil. Approximately 0.08 kg of catalyst are consumed for each barrel of gas oil processed. Figure 1a shows a photograph of a commercial FCC system comprised of a riser reactor and a catalyst regenerator. In the schematic diagram shown in Figure 1b, gas oil is fed into the bottom of the riser in contact with high-temperature catalyst particles recycled from the regenerator to the riser. The gas oil is evaporated, carrying catalyst particles along with it throughout the riser, where cracking reactions take place. The product of the reactions is then sent to the fractionator; the spent catalyst particles are stripped by steam and recycled back to the regenerator.

The solids in this system are processed with gas in various forms or modes. For example, within the riser, gas and solids are in the dilute pneumatic transport mode, whereas within the regenerator, gas and solids are in the dense, turbulent

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Professor Fan is the principal inventor (with R. Agnihotri) of a patented process, "OSCAR," for flue gas cleaning in coal combustion and is the Project Director for the OSCAR commercial demonstration, funded at $8.5 million as Ohio Clean Coal Technology, currently taking place at Ohio McCracken power plant on the Ohio State University campus.

He has served as thesis advisor for two BS, twenty-nine MS, and forty-two PhD students at Ohio State, and is a Fellow of the American Association for the Advancement of Science.

* *Part 2 of this lecture will appear in the Spring 2000 issue of CEE.*

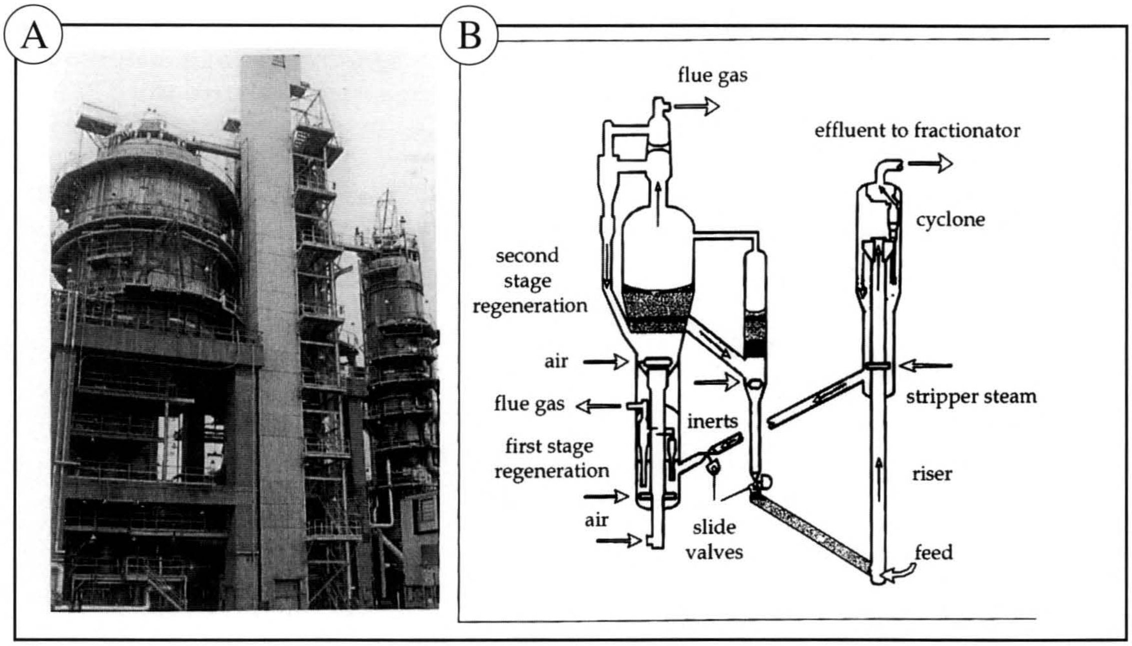

Figure 1.

FCC systems for gas-oil cracking:

(a) Photograph of Equilon (formerly Texaco) commercial FCC unit plant at Los Angeles Refinery (kindly provided by F. Bavarian of Texaco);

(b) Schematic of the system.

fluidization mode. In the catalyst recycle loop, there are dense-phase standpipe solids flow and inclined pipe solids flow.

Solids processing is also involved in chemical synthesis, such as the production of polyethylene/polyolefin. Using the UNIPOL process[2] as an example (see Figure 2), catalyst, cocatalyst, monomer, and comonomer are introduced into a turbulent fluidized bed, where polymerization reactions take place. In the reactor, polymer particles grow in size through chain reactions and eventually reach the final polyethylene size average of 600μm.

Solids processing is also involved in a number of other industries. For example, it is used in physical operations such as powder coating, drying, and mixing. It is also used in energy and environmental systems, e.g., coal combustion and gasification, and incineration of solid wastes, and in metallurgical and mineral processing such as titanium dioxide production. In biological systems it is used, for example, in ethanol fermentation. Overall, solids processing systems are responsible for well over \$100 billion of the chemical and petrochemical market economy annually.

Many students take part in industrial internships and co-op programs. These students and many engineering graduates employed in industry frequently find themselves involved in solids processing, for which they have not been well prepared through regular course work. If we examine the typical undergraduate educational material pertaining to solids processing, we will note that this material is often limited to single-particle behavior (drag, terminal velocity, heat and mass transfer), fixed beds, catalytic and non-catalytic fluid-particle reaction kinetics, and particulate reaction engineering. In the latter, solids particles are often treated the same way as gases or liquids. As a result, the unique characteristics of particle mechanics are not introduced into the analysis of particulate reaction systems. Indeed, very little is discussed on core topics relating to solids processing and particle technology such as

- Particle characterization
- Particle formation
- Size enlargement and agglomeration
- Comminution and attrition
- Tribology, friction, and interparticle forces
- Fluidization and multiphase flow
- Solids flow, handling, and processing
- Powder mechanics and slurry rheology
- Colloids and aerosols

The importance of particle technology education and research was brought to the attention of the industrial and academic communities through the perseverance of such organizations as the American Filtration Society and the Particle Technology Forum of the AIChE in the early 1990s. Subsequent articles in *Chemical Engineering Progress* (*CEP*)[3] and *Chemical Engineering Education* (*CEE*)[4] have contributed to increasing awareness of this topic. As a result

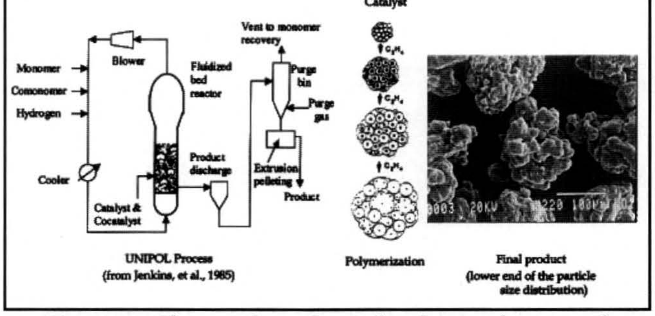

Figure 2. *Chemical synthesis for the production of polyethylene/polyolefin (UNIPOL process).*

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of the Fluid-Particle Processes Workshop at the ASEE Summer School for Chemical Engineering Faculty (Snowbird, Utah, 1997), the following articles and reprints related to particle technology education were published in the spring issue of *CEE* in 1998:

- "Teaching Fluid-Particle Processes: A Workshop Report," R.H. Davis, L.-S. Fan
- "Industrial Perspective on Teaching Particle Technology," R.D. Nelson, Jr., R. Davies
- "Particle Technology Concentration at NJIT: An NSF-CRCD Program," R.N. Dave, I.S. Fischer, J. Luke, R. Pfeffer, A.D. Rosato
- "CFD Case Studies in Fluid-Particle Flow," J.L. Sinclair
- "Experiments, Demonstrations, Software Packages, and Videos for Pneumatic Transport and Solid Processing Studies," G. Klinzing
- "Undergraduate Teaching in Solids Processing and Particle Technology: An Academic/Industrial Approach," G.G. Chase, K. Jacob
- "Particle Science and Technology Educational Initiatives at the University of Florida," A.E. Donnelly, R. Rajagopalan

The authors of the articles above are heavily engaged in fluid-particle education and research, and therefore the articles are most pertinent to the point of the present discussion. Recently, federal-, state-, and/or industry-funded research and education centers were formed (*e.g.,* NSF/ERC in Particle Science and Technology at the University of Florida, NJIT/Rutgers State Program on Particle Technology, and the Ohio Board of Regents Universities Consortium on Fine Particle Processing). New web sites (*e.g.,* http://www.erc.ufl.edu/erpt/), new instructional modules (*e.g.,* "Introduction to the Principles of Size Reduction of Particles by Mechanical Means," by Klimpel[5]), introductory textbooks (*e.g., Introduction to Particle Technology,* by Rhodes[6]), advanced textbooks (*e.g., Principles of Gas-Solid Flows,* by Fan and Zhu[7]), and CD-ROMs (*e.g.,* "Laboratory Demonstrations in Particle Technology," by Rhodes and Zakhari[8]) have been published as a result of the growing interest and acknowledged importance of particle mechanics.

I would now like to present some problems that I have noted in my experience in teaching fluid-particle systems that are confusing to students. I will give two examples.

► *Log-Normal Distribution*

There are three distribution functions that are commonly used to describe particle size distributions, *i.e.,* normal distribution, log-normal distribution, and Rosin-Rammler distribution. The log-normal distribution is particularly confusing to students.

In examining the log-normal distribution, it is noted that it can be expressed in two different equations, depending on whether the random variable is d (Eq. 1) or $\ln d$ (Eq. 2), as given by

$$f_N(d) = \frac{1}{\sqrt{2\pi}\sigma_{dl} d} \exp\left[-\frac{1}{2}\left(\frac{\ln d - \ln d_{50}}{\sigma_{dl}}\right)^2\right] \quad (1)$$

or

$$f_N(\ln d) = \frac{1}{\sqrt{2\pi}\sigma_{dl}} \exp\left[-\frac{1}{2}\left(\frac{\ln d - \ln d_{50}}{\sigma_{dl}}\right)^2\right] \quad (2)$$

Here, d is the diameter of the particle, d_{50} is the median diameter, and σ_{dl} is defined as $\ln(d_{84}/d_{50})$, where d_{84} is the diameter for which the cumulative distribution curve has the value of 0.84. Further, Eq. (2) is the usual expression for the normal distribution with the random variable taken as $\ln d$. The values of $\ln d_{50}$ and σ_{dl} in Eq. (1) or (2) represent the mean and standard deviation of the $\ln d$ distribution, but they are not representative of those of the d distribution. Students are often confused by the two forms of Eqs. (1) and (2) and by the fact that the arithmetic mean of the $\ln d$ distribution is not equal to the arithmetic mean of the d distribution, nor does it equal the natural log of the arithmetic mean of the d distribution; likewise the standard deviation of the $\ln d$ distribution is not equal to that of the d distribution.

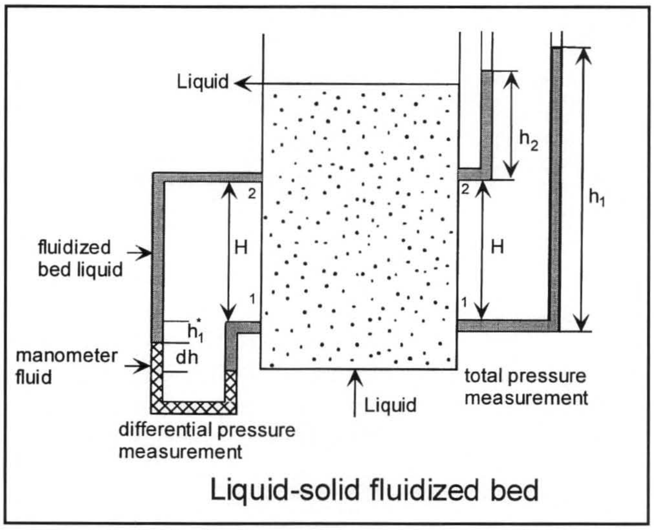

Figure 3. *Pressure-drop measurement for a liquid-solid fluidized bed.*

► ***Dynamic Pressure Drop***

When a manometer is used to measure pressure drop of a suspended particle flow, *e.g.,* a liquid-solid fluidized bed, the pressure drop is measured by $(\rho_m - \rho_l)gdh$ where ρ_m is the density of the manometer fluid and dh is the level difference between the manometer fluid and the liquid in the fluidized bed, as shown on the left-hand side of the manometer arrangement in Figure 3. The pressure drop measured in this manner is known as the differential pressure drop. Students most often question whether the differential pressure drop represents the dynamic pressure drop, ΔP_d, or the total pressure drop ΔP_t, as defined by

$$\Delta P_t = P_{1,t} - P_{2,t} \tag{3}$$

$$\Delta P_d = \Delta P_t - \rho_l gH \tag{4}$$

A force balance on the manometer fluid yields

$$P_{1,t} + \rho_l g\left(h_l^* + dh\right) = P_{2,t} + \rho_l gH + \rho_l gh_l^* + \rho_m gdh \tag{5}$$

Rearranging Eq. (5) gives

$$\Delta P_t - \rho_l Hg = (\rho_m - \rho_l)gdh \tag{6}$$

Thus, we have

$$\Delta P_d = (\rho_m - \rho_l)gdh \tag{7}$$

That is, it measures the dynamic pressure drop.

The total pressure drop can be measured with the manometer open to the atmosphere, as shown in the right-hand side of the manometer arrangement in Figure 3. Frequently, pressure transducers are used for pressure-drop measurements. In this situation, it is essential that proper calibration of the transducer be made so that it reflects the correct type of pressure drop being measured.

Correct identification of either type of pressure drop is important, as they are often used to calculate the volume fraction of the particle, ε_s, or liquid, ε_l, in the bed through the relationships

$$\Delta P_t = (\varepsilon_s \rho_s + \varepsilon_l \rho_l)gH \tag{8}$$

$$\Delta P_d = \varepsilon_s(\rho_s - \rho_l)gH \tag{9}$$

COMPARISONS OF MECHANICS OF FLOW BETWEEN SOLIDS AND LIQUIDS

Phenomenologically, particles and fluids are similar in that they both can flow, but there are distinct differences between their mechanics of flow. For example, particles and fluids respond to stress differently. Solids can transfer shearing stresses under static conditions, while liquids cannot transfer shearing stresses without flowing. For a slow motion of solids, the shear stress varies with the normal stress rather than with shear rate. For a liquid flow, the opposite is true. Solid particles can be consolidated by their cohesive strength induced by internal friction, while there is no internal friction in liquids to sustain their consolidation. Therefore, solid particles can form a heap with a non-zero angle of repose, whereas liquids lie flat under static conditions.

When particles or liquids are placed vertically in a pipe with both ends of the pipe open, the wall shear stress can provide the predominant support for the particle weight. Therefore, to maintain solid particles stationary in the pipe, only a small force needs to be applied to the bottom of the pipe.[9] This is not the case for a liquid. The coherence of the

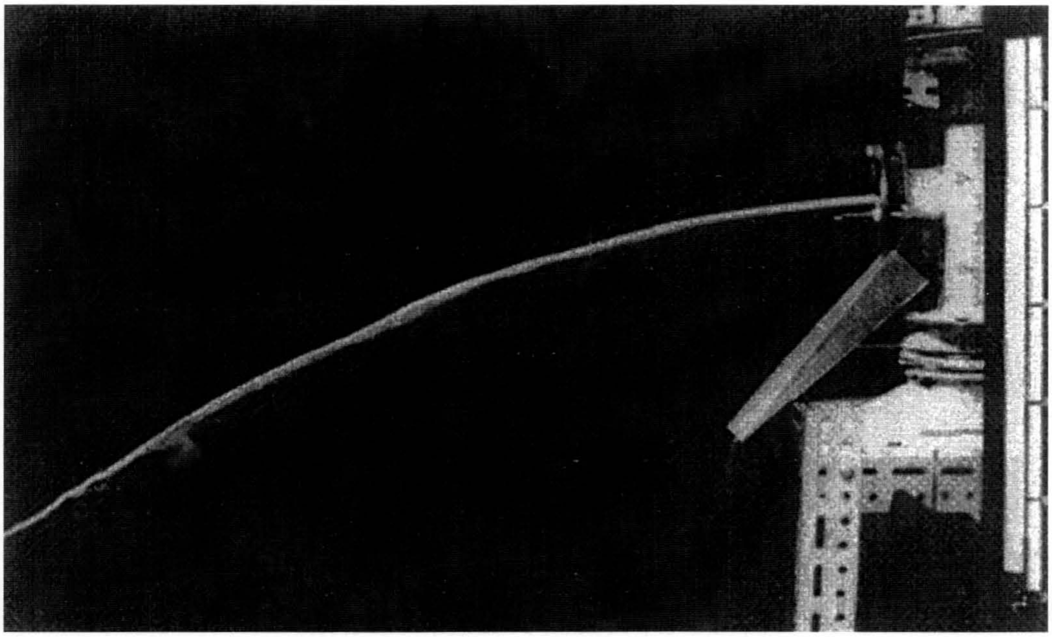

Figure 4.

Particle jet (alumina, 75 μm) formed from a nozzle (3.1 mm in diameter) in an air-fluidized bed (from Martin and Davidson;[10] reproduced with permission).

particles can also be demonstrated by a particle jet[10] when formed from a nozzle in a gas-solid fluidized bed of 75 μm alumina particles, as shown in Figure 4. The coherence of the jet is clearly seen in the figure. The liquid jet from a liquid column is less coherent.

Despite the long history of practice in particle mixing, the phenomena involved remain fascinating and puzzling.[11] Taking the particle band formation in a rotating tube with a binary mixture of particles as an example, a single band or multiple bands would form transiently in a binary mixture of certain particle sizes, weight ratios, and particle volume fractions in the tube. Figure 5 shows single-band and double-band formation of small glass beads (d_p = 0.15 mm, colored white, 30 vol% in the particle mixture) in the presence of large glass beads (d_p = 1.0 mm, colored red, 70 vol% in the particle mixture) with a rotation speed of 60 RPM. The volume fraction of the particle mixture in the tube is 70%. The tube is of 3.1 cm ID and 36 cm in length. The single band forms first and disappears, and then a double band forms. Although some theories, *e.g.*, percolation theory, have been used to explain the particle migration phenomenon, so far there is no overwhelmingly convincing mechanistic explanation of the complex phenomenon exhibited by such a simple experiment.

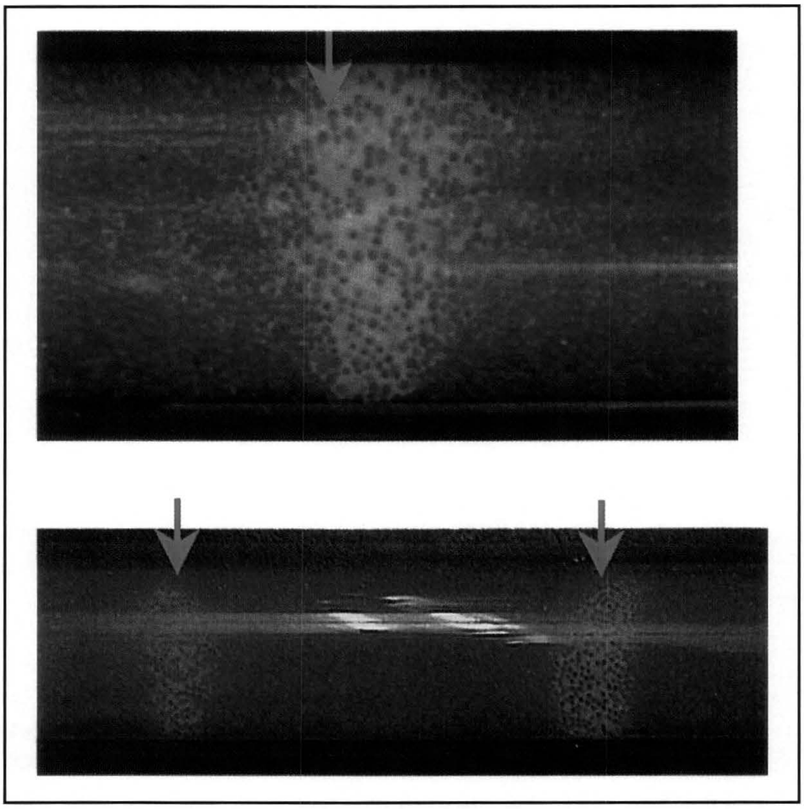

Figure 5. Illustrations of particle-band formation.

SAMPLE SUBJECTS OF INTERDISCIPLINARY NATURE

Probably the most effective way to impart knowledge of such an interdisciplinary topic as particle mechanics to students is through several required chemical engineering courses including fluid mechanics, heat and mass transfer, and reaction engineering, in which clear distinctions can be made between particle and fluid behavior. Once students are vested with the background knowledge relating to particle mechanics, they can choose to take technical-elective courses in chemical engineering or other engineering disciplines that cover some specific aspects of particle-related subjects. In the following, I have chosen hopper and standpipe systems as examples to illustrate the relevance of powder mechanics to a fundamental understanding of powder flow in these systems. These examples are introduced so that students will be familiar with subjects of an interdisciplinary nature.

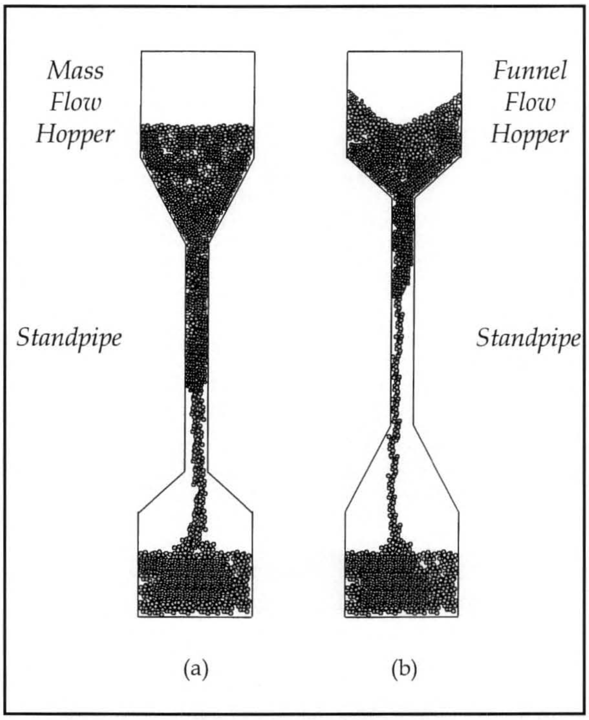

Figure 6. *A device showing mass-hopper flow, funnel-hopper flow, and standpipe flow.*

Hopper and standpipe flows can be demonstrated with a simple experiment. Figure 6 shows a photograph of a device partially filled with table salt. The device has hoppers connected by a standpipe. Figures 6a and 6b show two different hopper flow patterns. For hoppers with a small apex angle (Figure 6a), solid particles flow downward uniformly across the whole cross section, forming a flat surface that is known as a mass-flow hopper. For hoppers with a large apex angle (Figure 6b), solid particles at the central location flow faster than those at the wall, forming a funnel-shaped free surface, known as a funnel-flow hopper. The standpipe flow in the figure shows moving bed transport followed by suspension transport of solids with a larger moving bed region for the mass-flow hopper than for the funnel-flow hopper.

The onset of powder motion in a hopper is due to stress failure in powders. Hence, the study of hopper flow is closely related to understanding the static stress distribution in a hopper.[12] The local distributions of static stresses of powders can only be obtained by solving equations of equilibrium. From stress analyses and suitable failure criteria, the rupture locations in granular materials can be predicted. As a result, the flowability of granular materials in a hopper depends on the internal stress distributions determined by the geometry of the hopper and the material properties of the solids.

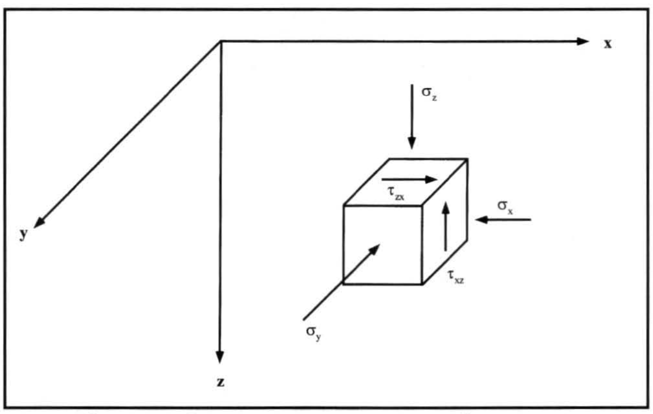

Figure 7. *Stress components in a plane-strain problem in the x-z plane.*

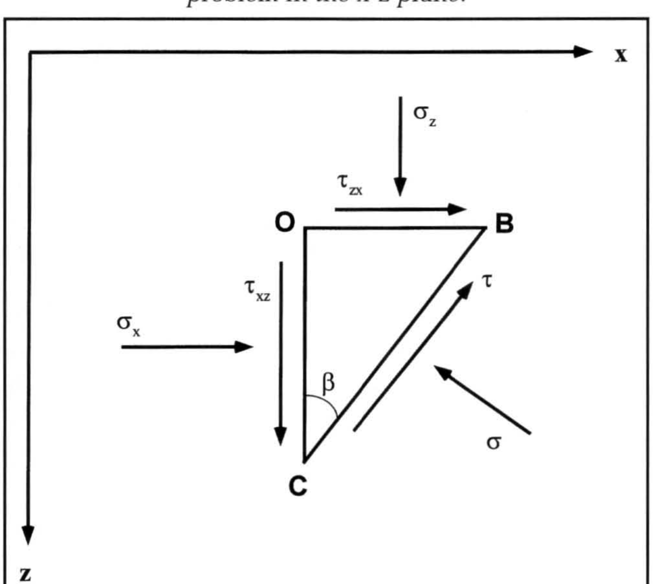

Figure 8. *Equilibrium of stress components on a differential element.*

Stress analysis of solid materials is a typical subject for engineering mechanists or soil mechanists in civil engineering, but chemical engineers also need to be familiar with the subject in order to be able to quantify moving-bed transport flow of solid particles. Here, students need to learn the Mohr Circle for plane stresses and the Mohr-Coulomb failure criterion, which can be illustrated as follows.

● ***Mohr Circle for Plane Stresses***

We consider stresses on a point represented by a cubic differential element. For simplicity, we examine only the stresses acting on a plane, say the x-z plane, of a cube, as shown in Figure 7. The stress tensor, expressed in Cartesian coordinates, takes the form

$$T = \begin{bmatrix} \sigma_x & 0 & \tau_{xz} \\ 0 & \sigma_y & 0 \\ \tau_{zx} & 0 & \sigma_z \end{bmatrix} \tag{9}$$

where the σ' s are normal stresses (compressive stresses are considered as positive), and the τ' s are shear stresses. From Hooke's law and assuming no displacement in the y-direction, we have

$$\sigma_y = \nu(\sigma_x + \sigma_z) \tag{10}$$

where ν is Poisson's ratio. In addition, from the conservation of angular momentum, T is found to be a symmetric tensor so that $\tau_{xz} = \tau_{zx}$. Thus, the plane stress tensor in Eq. (9) depends solely on σ_x, σ_z, and τ_{xz}. As shown in Figure 8, the force balance on the differential element results in the stress relationships on the BC plane, as given by

$$\begin{aligned} \sigma &= \sigma_x \cos^2\beta + \sigma_z \sin^2\beta + 2\,\tau_{xz} \sin\beta\cos\beta \\ \tau &= \tau_{xz}\left(\cos^2\beta - \sin^2\beta\right) + \left(\sigma_z - \sigma_x\right)\sin\beta\cos\beta \end{aligned} \tag{11}$$

where β is the angle between the normal of the BC plane and the x-axis. From Eq. (11), two perpendicular planes can be found on which the shear stress vanishes (*i.e.,* $\tau = 0$). The directions of these planes are known as the principal directions and the corresponding normal stresses as the principal stresses. The angle for the principal directions, β_{pr}, is determined from Eq. (11) as

$$\beta_{pr} = \frac{1}{2}\tan^{-1}\left(\frac{2\,\tau_{xz}}{\sigma_x - \sigma_z}\right) \tag{12}$$

which yields the principal stresses as

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_z}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_z}{2}\right)^2 + \tau_{xz}^2} \tag{13}$$

If the principal directions are taken as the x- and z-axes, *i.e.*, $\sigma_x = \sigma_1$; $\sigma_z = \sigma_3$, Eq. (11) reduces to

$$\sigma_x = \sigma_1;\ \sigma_z = \sigma_3$$
$$\sigma = \sigma_1 \cos^2 \beta + \sigma_3 \sin^2 \beta$$
$$\tau = (\sigma_3 - \sigma_1)\sin\beta\cos\beta \tag{14}$$

which is the equation of a circle in $\sigma - \tau$ coordinates as shown in Figure 9. This circle is known as the Mohr circle. The direction and the magnitude of stresses on any plane can be determined graphically from the Mohr circle. As shown in Figure 9, the normal stresses on the principal planes are of maximum or minimum values.

● ***Mohr-Coulomb Failure Criterion and Coulomb Powder***

The most common failure criterion for granular materials is the Mohr-Coulomb failure criterion. Based on this criterion, the material fails along a plane only when a critical combination of normal and shear stresses exists on the failure plane. This critical combination, known as the Mohr-Coulomb failure criterion, is given by

$$\tau = c + \sigma \tan \eta \tag{15}$$

where c is the cohesion defined as the resistance of the material to shear under zero normal load and is a result of the intermolecular cohesive forces, frictional forces, and other forces acting on the material, and η is the angle of internal friction of the material, which corresponds to the maximum static friction condition as the bulk solids start to slide on themselves at the state of incipient failure.

The Mohr-Coulomb failure criterion can be recognized as an upper bound for the stress combination on any plane in the material. Consider points A, B, and C in Figure 9. Point A represents a state of stresses on a plane along which failure will not occur. On the other hand, failure will occur along a plane if the state of stresses on that plane plots a point on the failure envelope, *e.g.*, point B. The state of stresses at point C cannot exist since it lies above the failure envelope. 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, YL.

A rigid-plastic powder that 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. The Mohr-Coulomb failure criterion underlies a basic principle that quantifies important hopper design variables such as

- *Critical major principal stress in a stable arc,* σ_a *(see Figure 10)*
- *Hopper (half) apex angle,* φ_w *(see Figure 10)*
- *Minimum outlet dimension of the hopper*

Industrial accidents do occur frequently in hopper flow due to the failure of hopper operators to recognize the stress behavior acting on a stable arc (Figure 10), which blocks the solids flow.

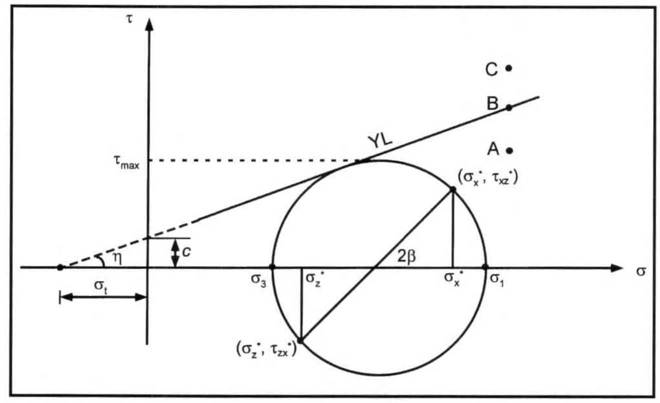

Figure 9. *Mohr circle and Mohr-Coulomb failure envelope.*

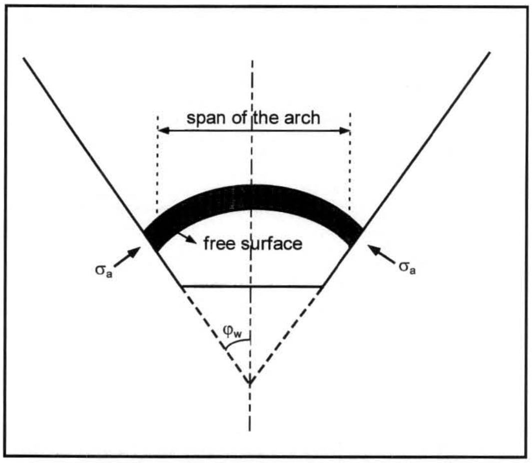

Figure 10. *Arching (or doming) at the hopper outlet.*

● ***Standpipe Flows***

Standpipe flow refers to the downward flow of solids with the aid of gravitational force against a gas pressure gradient. Gas flow is in the upward direction with respect to the downward-flowing solids; relative to the wall, the actual direction of the flow of gas can be either upward or downward.[13] Solids fed into a standpipe are often from hoppers, cyclones, or fluidized beds. A standpipe can be either vertical or inclined, and its outlet can be simply an orifice or can be connected to a valve or fluidized bed. There can be aeration along the side of the standpipe. Frequently, the following assumptions are used in the analysis of a vertical standpipe flow:

- *Both solids and gas are regarded as a pseudocontinuum throughout the standpipe system.*
- *Motions of solids and gas are steady and one-dimensional (in the axial direction).*
- *Solids can flow in either moving-bed mode or dilute-suspension mode. Solids stresses among particles and between particle and pipe wall are considered in the moving bed*

flows but neglected in the dilute suspension flows.

- *The gas can be regarded as an ideal gas, and the transport process is isothermal.*

The cylindrical coordinate system selected for the standpipe is shown in Figure 11. For a one-dimensional steady motion of solids, the momentum equation of the particle phase can be written as

$$\rho_p(1-\alpha)u_{zp}\frac{du_{zp}}{dz}=\rho_p g(1-\alpha)-\frac{d\sigma_{pz}}{dz}-\frac{2\tau_{pw}}{R_s}+F_D \quad (16)$$

where α is the volume fraction of the gas phase; σ_{pz} is the normal stress of solids, τ_{pw} is the shear stress of solids at the pipe wall, F_D is the drag force per unit volume, and R_s is the radius of the standpipe. As solids flow can be in either a moving packed bed mode or a suspension transport mode, Eq. (16) can be simplified as

- *For a moving packed bed mode, α is constant.*
- *For a suspension transport mode, σ_{pz} is negligibly small.*

The general momentum balance for the gas phase can be expressed as

$$\frac{dp}{dz}=-F_D \quad (17)$$

where p is the pressure.

For a simple standpipe system, different flow patterns of steady flow may exist, depending on the ranges of operational parameters of the system. This phenomenon is known as steady-state multiplicity.[14] The steady-state multiplicity is considerably more complicated when gas aeration takes place from the side of a standpipe for controlling the solids flow rate. Such gas aeration is common in industrial operation.

CONCLUDING REMARKS

I would like to conclude this part of my lecture with the following thoughts:

- *Particle technology as exemplified by fluidization and fluid-particle systems is an important interdisciplinary area. Chemical engineers play a key role, as there are many industrial applications in the chemical process industries.*
- *Education in particle technology is important from both the industrial and the academic perspectives. Significant progress in education and research in this area has been made recently, such as increased textbook publications and increased industrial recruiting of U.S.-educated graduates—but much remains to be done.*
- *The most effective way to introduce particle technology materials to chemical engineering students is through such existing required courses as transport phenomena and reaction engineering.*

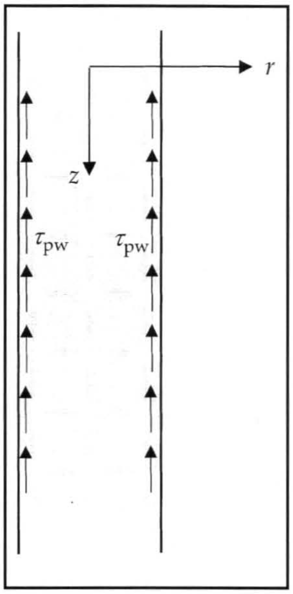

Figure 11. *Coordinate system for one-dimensional standpipe flow.*

ACKNOWLEDGMENTS

This lecture is dedicated to the memory of Professor Shao-Lee Soo of the University of Illinois, Urbana. I am grateful to Prof. Fernando Muzzio for insightful discussions on powder mixing and band formation, and to Dr. Fashad Bavarian for providing the FCC unit photograph used in Figure 1 and the information concerning commercial operation of FCC units. I am also indebted to Prof. Jack Zakin and my research group members, Dr. Jianping Zhang, Mr. D.-J. Lee, Mr. Brian McLain, Mr. Will Peng, and Mr. Guoqiang Yang, who have provided constructive feedback in the preparation of this lecture material.

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