PARTICLE TECHNOLOGY DEMONSTRATIONS

For The Classroom and Laboratory

SIMON M. IVESON, GEORGE V. FRANKS
University of Newcastle • Callaghan, NSW 2308, Australia

One of the joys of teaching a course on powder technology is the abundance of quick and simple experiments that can be used in lectures to demonstrate the fundamental phenomena being discussed. These can be used as breaks part way through a lecture or as an interest-arousing introduction to a new topic. Demonstrations can be used to highlight the often counter-intuitive behavior of powders by asking the students to break into groups and try to predict *a priori* how they expect a given system to behave. The often quite different behavior that they subsequently observe will then challenge them to understand the causes of their misconceptions and arouse their interest in the lecture material.[1,2]

There are more than enough such demonstrations to fill a spot in every lecture of a one-semester introductory course on powder technology. Most, however, are referred to only in passing in references scattered throughout the literature[e.g.,3-6] or are passed on by word-of-mouth from one practitioner to another. Klinzing[7] has provided a partial list of such demonstrations, and a recent CD by Rhodes and Zakhari[8] contains video clips of many others.

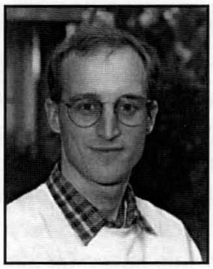
This paper seeks to provide a comprehensive compilation of demonstrations to act as a reference for new instructors in particle technology. Demonstrations related to wet-powder systems are presented first, followed by dry-powder systems. Wet-powder system behavior covered includes single-particle settling, hindered and lamella settling, sedimentation, the effect of surface chemistry on slurry rheology, powder wetting, and wet-granule coalescence. Dry-powder system behavior covered includes flow from hoppers, percolation and elutriation segregation, the "Brazil-nut" effect, surface friction, and powder compaction. Where possible, the source of the ideas presented is acknowledged, either by reference to a publication or mention of the person who first told the authors. Many of these ideas have been around so long, however, that it is difficult to identify their origin, and we apologize in these cases for not acknowledging their original source.

WET-POWDER SYSTEMS

Single-Particle Settling *(in-class demonstration)*

Most courses on fluid-particle interactions begin by examining the settling of a single spherical particle. The effect of fluid viscosity can be demonstrated by using glass marbles in two identical perspex tubes about 40 cm long, one filled with water and the other with glycerol (or any other transparent viscous fluid).[9] Start by asking the students in groups to estimate the settling time of each marble. Most will correctly guess that the marble will settle more slowly in the glycerol. When asked why, they will probably refer to either glycerol's greater density or its greater viscosity compared to water.

If students think that density difference is the cause, then a simple buoyant force balance can be used to calculate how long it would take the marble to fall under the influence of gravity alone. For $\rho_{water} = 1$ g/cm^3, $\rho_{glycerol} = 1.25$ g/cm^3 and $\rho_{glass} = 2.5$ g/cm^3, the increase in fall time in the glycerol due to its greater density would be only 10%. The calculated set-



Simon Iveson *completed his Bachelor of Chemical Engineering in 1992 and his PhD in 1997, both at the University of Queensland. Since then he has been a research fellow and lecturer in the Department of Chemical Engineering at the University of Newcastle. His research interests are in the field of particle technology, with his focus being on the agglomeration of fine particles by the addition of liquid binders.*

George Franks *completed his BS in Materials Science and Engineering at MIT in 1985 and his PhD in Materials at the University of California at Santa Barbara in 1997. He has been a senior lecturer in the Chemical Engineering Department at the University of Newcastle since 1999. His research interests include colloidal processing of ceramics, mechanical behavior of wet powder bodies, and mineral processing processes such as flocculation.*

tling times for a 40-cm long tube are of the order 0.4 s, which is less than the approximate 1 sec and 10 sec observed in practice. Clearly, buoyancy effects alone do not explain the speed at which the marbles fall.

At this stage (if they have not already done so), some students may recall the concept of viscosity and fluid drag from their previous fluids courses. This can lead to a brief review of drag coefficients, terminal velocities, etc. For the marble in glycerol, the Reynolds number is low and Stokes' law ($C_D = 24/\mathrm{Re}$) applies, Hence, the terminal settling velocity V_T of the marble is given by

$$V_T = \frac{(\rho_P - \rho_L)d^2 g}{18\,\mu} \tag{1}$$

where ρ_P and ρ_L are the density of the particle and liquid, d is the marble diameter, g is gravitational acceleration, and μ is the fluid viscosity.

For the marble in water, the Reynolds number is of order 10^5, giving a drag coefficient of approximately $C_D = 0.44$. The terminal settling velocity is given by

$$V_T = \sqrt{\frac{4(\rho_P - \rho_L)dg}{3\rho_L C_D}} \tag{2}$$

Thus, the difference in viscosity between glycerol ($\mu \approx 1$ Pa·s) and water ($\mu = 0.001$ Pa·s) can be shown to be the major cause of the difference in their settling velocities.

Some students may also think of another cause for the slower than expected fall of the marbles, namely hindering caused by the back flow of displaced liquid up the tube walls as the marble moves past. This is illustrated in the next demonstration.

<u>Hindered and Lamella Settling</u> *(in-class demonstration)*

Hindered settling can be illustrated using a pair of perspex tubes filled with the water, the first containing only a single small bead and the second a large group of identical beads. The settling rates of the two systems can then be compared, to illustrate how the presence of many particles reduces the settling speed. Explain how settling is hindered by the need for the displaced water to flow back up through the bed of particles (see Figure 1a); then ask the class to think of ways to increase the rate of particle settling.

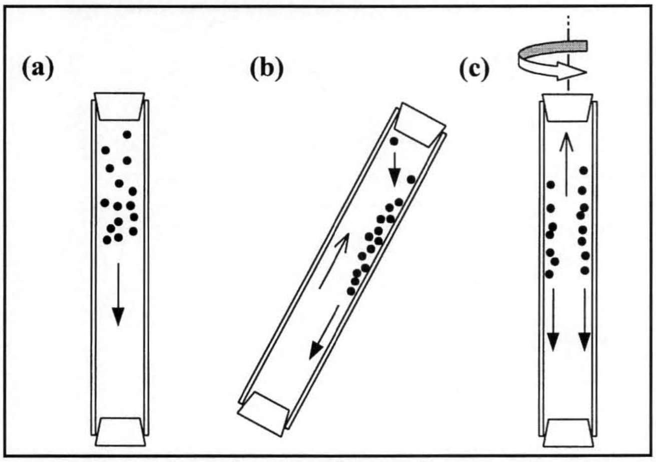


Figure 1. *(a) Hindered settling and ways to speed up settling by (b) tilting the tube or (c) shaking it in a circular motion.*

One way to accelerate settling is to tilt the tube slightly so that particles have only a short distance to fall to reach the tube wall, where they can then slide down quickly as the displaced water flows unhindered above (Fibure 1b).[10] This illustrates how lamella settlers operate. Another method is to shake the tube in a horizontal circular motion while keeping it vertical. The centrifugal force moves particles to the wall, leaving the center of the tube free for displaced water to flow upward, thus allowing the particles to settle more quickly down the sides (Figure 1c). This is similar to what happens inside a hydro-cyclone.

<u>Sedimentation and Flocculation</u> *(in-class demonstration)*

The different types of sedimentation behavior can be easily demonstrated by filling three tall jars with Type I, Type II, and colloidal (non-settling) particle suspensions. Shake the jars at the start of the lecture and point out the different behaviors. Type I suspensions are those that form three zones during settling—a clear liquor above the settling particles (zone A), a suspension of particles of the same concentration as the initial suspension (zone B), and a settled bed at the base (zone S). During settling, the interface between zones A and B falls and the interface between zones B and S rises, until the two meet and zone B disappears.

Type II suspensions form four zones during settling. In addition to zones A, B, and S, there is a zone of variable concentration (zone E) that forms between zones B and S. Colloidal particles do not settle out at all. Toward the end of the lecture, once students are convinced that the colloidal particles are not going to settle, a flocculant can be mixed into the suspension to demonstrate the resultant dramatic improvement in settling behavior.

<u>Sedimentation and Flocculation</u> *(laboratory module)*

A laboratory module based on particle settling is also possible. Give the students three or four samples of silica of different average particle size ranging from about 1 micron to about 250 microns. The size distributions should be monomodal and less than one decade in breadth. Prepare 250 ml of a suspension of 3 wt% solids for each powder in distilled water in 150-ml graduated cylinders. Adjust the pH to 8.0 with NaOH so that the silica is well dispersed. Shake the cylinders and observe the sedimentation. Measure the time required for the first noticeable formation of the sediment bed. Measure the height of the interface between the clear supernatant and the suspension as a function of time.

Students will notice that the micron-sized silica does not settle appreciably in the time available. Mention that for particles smaller than about 0.1 microns, Brownian motion dominates gravitational settling so that a stable suspension results. Use a suitable cationic polymer to flocculate the suspension so a clear supernatant results.

The students should calculate the size of the largest particles in the sample assuming that the time for the first noticeable sediment bed to form corresponds to the time that the largest particles settle the distance from the top of the tube to the bottom. Using that velocity and Stokes' law or Newton's law, the size of the largest particles can be calculated. They should also calculate the size of the smallest particles based on the velocity of the suspension/clear supernatant interface. Then provide them with the measured particle size distributions of the silica samples and ask them to compare their calculated largest and smallest particle sizes with the size distribution data provided. The comparison is surprisingly good.

Interparticle Force Effects on Colloidal Suspension Rheology
(laboratory module)

Many chemical engineers are not trained to consider how the chemical nature of the fluid medium can influence the rheological behavior of a suspension. pH is one of the easiest properties of a slurry to measure on-line and it can also dramatically affect suspension properties. A simple laboratory project that illustrates this effect by comparing the slumping behavior of zircon suspensions as pH is varied is shown in Table 1.

TABLE 1
Laboratory Module: Interparticle Force Effects on Colloidal Suspension Rheology

Few chemical engineers are trained to consider how the chemical nature of the fluid medium can influence the rheological behavior of a suspension. pH is one of the easiest properties of a slurry to measure on-line and it can also have a dramatic effect. The students measure the yield stress of a 0.40 volume fraction of solids zircon suspension over a range of pH values. The average size of the zircon is about 6 microns, so the interparticle surface forces are important in determining the rheological behavior. The density of zircon is 4400 kg/m^3. The yield stress can be measured by the slump method.[11] In this method, the paste-like suspension is filled into a cylinder on a flat surface and the cylinder is lifted off the suspension. The resulting slump height is measured (see Figure A1). The yield stress is related to the slump height by

$$\tau_Y = \rho g \frac{H}{2}\left(1 - \sqrt{\frac{s}{H}}\right) \tag{A1}$$

where τ_Y is the yield stress, ρ is the suspension density, g is the gravitational acceleration (9.8 m/s^2), and H and s are indicated in Figure A1.

The students should measure the yield stress of the suspension at pH values of approximately pH 7, pH 6, pH 5, pH 4, and pH 3. Use HCl and NaOH to adjust the pH, being careful not to overshoot the pH and come back since this will add salt to the suspension and thus affect the interparticle forces and thus the yield stress. Make sure the suspension is well mixed. The zeta potentials of the powder as a function of pH can be provided to the students as shown in Figure A2. Ask them to compare the measured yield stress values with the zeta potentials. They should comment on the behavior in their report.

Abbreviated Laboratory Report:

Figure A3 is a photo of the slump test being performed by one of the authors. The density of the suspension can be calculated as

$$\rho_{sus} = \phi\rho_{zircon} + \varepsilon\rho_{H20}$$

$$\rho_{sus} = 0.4\,(4400\ \text{kg}/\text{m}^3) + 0.6\ (1000\ \text{kg}/\text{m}^3) = 2360\ \text{kg}/\text{m}^3$$

The initial cylinder height (H) was 0.103 m. The slump (s) was measured with a ruler over a range of pH values from 3 to 7. The measured slump was used to calculate the yield stress (using Eq. A1). The yield stress is plotted against pH in Figure A4. The maximum yield stress correlates with the isoelectric point (where the zeta potential is zero). At this pH, only van der Waals attraction is operating between the particles creating a strong attraction and thus a high yield stress. The yield stress decreases as the pH is moved away from the isoelectric point. This is because as the charge on the surface of the particles increases, the electrical double layer repulsion also increases—thus reducing the magnitude of the attraction and thus the yield stress. See Shaw,[12] Hunter,[13] or Johnson, et al.,[14] for more details.

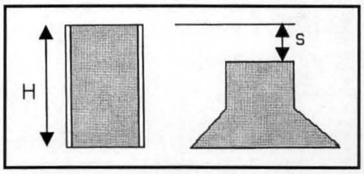


Figure A1. *Dimensions used in calculation of yield stress from slump test.*

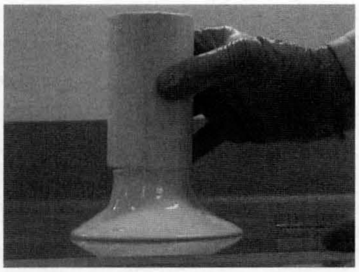


Figure A3. *Slump test in progress.*

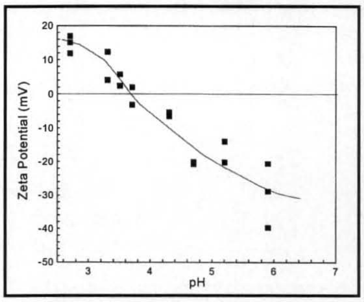


Figure A2. *Zeta potentials of zircon.*

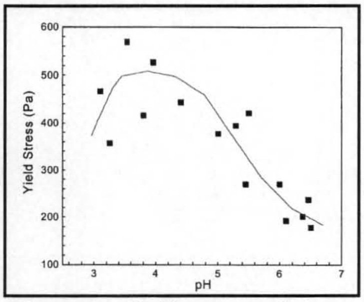


Figure A4. *Yield stresses of zircon.*

Wetting Behavior of Dry Powders
(in-class activity or laboratory module)

The wetting behavior of liquids on dry powders is important in applications such as mixing pigments into paints and the formation of agglomerates in agitated granulators. If the paint pigments do not wet well, then they will not disperse and instead form clumps of dry powder with trapped air inside. This detrimentally affects the paint quality. In granulation, the initial wetting behavior can have a large effect on the final product size produced in a granulator. Drops that penetrate the bed surface quickly are more likely to form individual nuclei—hence controlling the drop size controls the granule size. Slow penetration can lead to pooling of liquid on the powder surface, resulting in widely sized initial nuclei and widely sized final product.[15]

The rate of penetration of a liquid into the pores of a powder bed can be estimated by equating the capillary pressure driving force from the Young-Laplace equation

$$\Delta P_{cap} = \frac{2\gamma_{LV}\cos\theta}{r} \tag{3}$$

with the viscous resistance to laminar flow predicted from the Hagen-Poiseuille equation

$$\Delta P_{vis} = \frac{8\,u\mu l}{r^2} \tag{4}$$

to give a form of the Washburn equation

$$u = \frac{dl}{dt} = \frac{r\gamma_{LV}\cos\theta}{4l\mu} \tag{5}$$

where u is the liquid velocity, r is the effective pore radius, γ_{LV} is the liquid-vapor surface tension, θ is the solid-liquid contact angle, l is the length of pore filled, and μ is the liquid viscosity.

The effects of the parameters in Eq. (5) can be demonstrated by asking students to measure the penetration times of drops of water, honey, and alcohol onto a number of different powder beds, *e.g.,* coarse and fine sugar, ground pepper, and parmesan cheese (see Figure 2).[16] The coarse and fine sugar demonstrate the effect of pore size r. The rate of liquid penetration is approximately proportional to the particle size. Hence, the water penetrates the fine sugar more slowly than the coarse sugar. (Note: if an alternative powder that is insoluble in water is available in two different particle sizes, this may be preferable to using sugar.) The water and honey demonstrate how increasing viscosity μ slows down the rate of penetration. The water and alcohol on the cheese and pepper demonstrate the important effect of contact angle θ. Water does not wet or penetrate into either of these two powders, but alcohol wets both powders because it has a lower contact angle due to its lower surface tension, as seen by a force balance at the contact line between the three phases (the Young-Dupre equation)

$$\cos\theta = \frac{\gamma_{VS} - \gamma_{LS}}{\gamma_{LV}} \tag{6}$$

where the subscripts V, S, and L refer to the vapor, solid, and liquid phases, respectively.

A more comprehensive predictive model for the penetration time of a liquid drop onto a powder surface is presented by Hapgood, *et al.*[15] This could form the basis of a laboratory module for students in more advanced powder technology subjects where they would be required to measure the powder size and bed porosity.

Figure 2. *The non-wetting behavior of drops of water (front row) and sugar solution (middle row) compared with the rapid wetting of alcohol (back row) on a bed of grated parmesan cheese. Dye added to liquids to enhance visibility.*

Granulation Coalescence Behavior *(in-class demonstration)*

Wet granulation is performed by spraying a liquid binder onto an agitated powder mass. There is great interest in being able to predict the rate at which these granules grow as they are agitated. This depends on how likely it is for granules to coalesce during collisions of varying velocity.

In more advanced powder technology subjects, students may be introduced to two of the models available for predicting wet-granule coalescence. The Ennis model considers the collision of two equi-sized elastic spheres of radius r colliding head-on at a relative speed of 2u.[17] Each sphere is surrounded by a layer of fluid of viscosity μ and thickness h. The surface of each sphere has a roughness of h_a, which limits how close they can approach together. The spheres have a coefficient of restitution, e, and a density, ρ. Solving Newton's second law of motion, it is predicted that coalescence will occur when the viscous Stokes number, St_v, is less than some critical viscous Stokes number, St_v^*, where

$$St_v = \frac{8\rho r u}{9\mu} \quad \text{and} \quad St_v^* = \left(1+\frac{1}{e}\right)\ell n\left(\frac{h}{h_a}\right) \tag{7}$$

This model predicts that reducing the impact speed acts to *increase* the likelihood of coalescence. This behavior can be demonstrated by dropping a rubber ball from different heights onto a flat surface coated with a layer of honey. Below a threshold impact velocity (release height), the ball will not rebound.

Liu, *et al.,*[18] model colliding granules as elastic-plastic spheres that are initially surface dry, but then have liquid squeezed to the surface during collisions. This model predicts that low-velocity collisions are *less likely* to result in coalescence. This is because very little permanent plastic deformation occurs, and hence the area of contact formed between the two granules is very small and weak. This behavior can be demonstrated by dropping round balls of plasticine from different heights onto a flat surface (it helps if the plasticine is first warmed up by vigorously hand rubbing to make it softer). When the surface is inverted, the plasticine dropped from a low height will drop off because it did not deform, whereas plasticine dropped from a large height will remain stuck on for some time due to the greater amount of deformation forming a strong bond.

These two demonstrations serve to illustrate how coalescence behavior varies as consolidation changes granules from being low-density and deformable to high-density and non-deformable during the granulation process.

DRY-POWDER SYSTEMS

Hopper Flow *(in-class activity)*

A good hands-on introduction to a set of lectures on hopper flow is to split the class into groups of 2-4 students each and supply each group with some thin cardboard, paper, overhead transparencies, masking tape, scissors, a beaker of sand, and a pan (to prevent spilling sand all over the classroom floor). Give them 10 to 15 minutes to build a funnel (hopper) that must discharge a set mass of sand in a set time (starting full). Make up a hopper beforehand to check that the time limit is reasonable—try to set a required time that is long enough so that in trying to slow down the flow, the students will encounter problems such as arching or rat-holing. Offering an incentive such as a large chocolate bar as a prize for the group that gets closest to the set time adds some competitive spirit and fun to the exercise.

Wander between the groups as they try different designs and ask them what the design parameters are (hopper angle, opening size, and possibly the wall material), how the material is flowing (mass or funnel flow), and what problems they are encountering (*e.g.,* arching and rat-holing). Some groups may resort to things such as tapping or stirring the hopper in order to promote flow—discuss the practicalities and costs associated with this in an industrial setting.

Funnel Flow and Mass Flow *(in-class demonstration)*

The two main types of flow from hoppers are mass and funnel flow. In mass flow, the entire powder bed is in motion as the bin discharges. The first material put into the bin is also the first to come out. In funnel flow, material slips from the top surface down through a rat-hole in the center of the bin. The material at the bin walls is static—hence the first material put into the bin is often the last out of it. Jenike and Johanson[19] demonstrate the difference between mass and funnel flow by using an hourglass arrangement with a different hopper angle in each half (photograph can be found in reference 7). If the hopper angles and material are chosen correctly, the material will flow through the steep-angled hopper in mass flow and through the shallow-angled hopper in funnel flow. Fan[5] extends this idea by connecting the two hoppers by a long straight pipe. This column then acts as a standpipe, exhibiting regions of both moving bed transport and suspension transport of the solids.

Consolidation Effects of Powder Flow
(in-class demonstration)

One important aspect of powder technology that should be stressed to students is that, unlike most fluids, the behavior of powder systems is history-dependent. The effect of consolidation on flow behavior can be demonstrated by using some dish-washing powder and a funnel (the end of a plastic drink bottle works fine). Pour the powder into the funnel and when the exit is opened, then it will flow out easily. But if the powder is poured into the funnel and tapped before the exit is opened, it will have consolidated and no flow will occur when the exit is opened.[20] Mention should be made that other factors besides consolidation can also cause powder properties to change with time, such as capillary condensation, re-crystallization, and solid-state diffusion causing bonding at interparticle contacts.

Particle Dilation *(in-class demonstration)*

Osborne Reynolds[21] demonstrated shear-induced particle dilation using a manometer attached to a rubber bag filled with saturated sand. This experiment can be repeated using a clear plastic drink bottle (the type with the straw built into the cap so that it is easy to use while running or bike riding). Tightly pack the main bottle cavity with saturated sand and then top off with water until the water level reaches part-way up the tube. Ask students what will happen when the bottle is squeezed lightly. Counter to intuition, the water level actually drops. This is because the sand must dilate in order for particles to slide over one another. Water flows back into the powder bed as it dilates. This dilation behavior explains why sand "dries up" around your foot as you walk along the beach near the water's edge. Water is sucked away from the surroundings into the dilated sand matrix. When you lift your foot, this excess water then causes the sand to temporarily liquefy as the load is relaxed.[e.g.,22]

Wall Friction *(in-class demonstration)*

Powder bed behavior is different from that of a Newtonian fluid. In a fluid, some flow is always initiated when a shear force is applied, but powder beds offer a finite resistance to shear forces. This ability of a powder bed to support large loads can be demonstrated by asking students to push or pull a plunger up a tube that is gradually filled with more and more particles. Eventually, a stage of filling is reached beyond which they can no longer move the plunger—the force they are exerting is totally transferred by the particles to the wall of the tube. The force being exerted can be made visually evident by either including a spring balance on the pull cable[7] or by attaching a large spring on the shaft used to push the plunger up the column.[8] The implications of this behavior for the distribution of stresses on hopper walls and the difficulty of achieving uniform compaction in presses and dies can then be discussed.

A variation of this demonstration is to tape a thin sheet of tissue paper over one end of the tube, fill the tube with the powder, and then ask for a volunteer who thinks he or she is strong enough to push the powder bed through the tissue paper.

Segregation During Hopper Flow *(in-class demonstration)*

Another counter-intuitive behavior of powders is that flow and agitation often cause segregation, rather than mixing. Segregation during discharge of material onto a stockpile or into a hopper is a well-known phenomena. Many workers have used transparent 2D hoppers to demonstrate the "herring-bone" pattern formed due to a combination of *percolation* of fine particles and the lower *angle of repose* of the coarse particles (see Figure 3).[e.g.,7-8,19,23] The small particles percolate between the larger ones and this causes the fine ones to become concentrated in the center of the bed. During the periodic avalanches, large particles tend to roll further down the sloped surface of the bed because of their higher inertia and lower angle of repose. During these avalanches, the fine particles tend to settle out along the way. This causes the large particles to become concentrated at the base of the pile and also gives rise to the alternate bands of fine and coarse material.

A third, and less-often demonstrated mechanism of segregation is the elutriation or fluidization of ultra-fine particles in the upflowing air displaced by the downflowing solids. This can result in the ultra-fine particles settling out after the other particles and forming a layer on top of the heap. With an airtight 2-D hourglass arrangement and correct choice of particles, elutriation and percolation segregation phenomena can both be demonstrated simultaneously in the same apparatus. Figure 3 shows the demonstration midway through the discharge process. The back flow of air has elutriated the ultra-fines from the material flowing through the opening. The ultra-fines have instead formed a fluidized bed in the upper hopper. As a result, they are the last particles to flow from the hopper and hence they deposit on the top surface of the heap and flow down to the base at each edge.

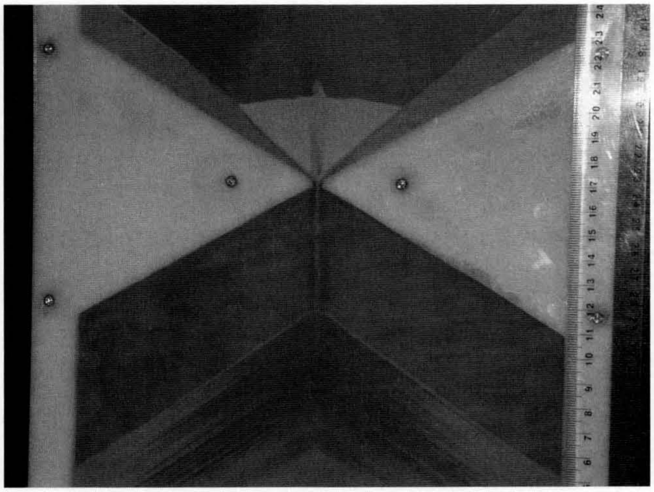


Figure 3. *Elutriation segregation of -20 micron hollow glass spheres (fluidized bed in the upper chamber) and formation in the lower chamber of a segregated "herring-bone" pattern of 200-400 micron beach sand (light color) and 50-100 micron hematite/iron-ore particles (darker color) during discharge from a sealed hopper.*

Before performing this demonstration, the students should be asked to predict where in the heap they think the different size fractions of material will be preferentially deposited. Then they can compare their predictions with the final result. Discuss the difficulties this behavior causes in obtaining representative samples from a poured heap of granular material. Representative samples can only be obtained by sampling at random intervals of time the full cross-section of a powder stream when it is in motion.

Vibrational Segregation *(in-class demonstration)*

The well-known "Brazil nut" effect can be easily demonstrated by covering a steel ball bearing with sand and then vertically tapping the container. The steel ball will rise to the surface, in spite of its greater density. The cause of this phenomena is not fully understood, but is believed to be linked to the inertia of the object, causing it to "punch through" the expanded bed during the upstrokes, whereas the packing of the powder prevents it from descending during the downstroke.[8,24-25]

Shinbrot and Muzzio[25] suggest a variation to this demonstration. If a low-density object is also added to the container, then the behavior of the two objects varies depending on whether the container is shaken horizontally or vertically. Under vertical vibrations, the steel ball rises and the low-density object sinks. Under vigorous horizontal vibrations, the steel ball sinks and the light object rises! The cause of this reversal is unclear, but is probably due to the bed dilating and becoming fluidized during horizontal vibration. The class can be asked to predict beforehand which of the two objects will rise or sink when the jar is "shaken" (without specifying how). Then the instructor can deliberately shake the jar in a direction that gives a result counter to the majority class opinion, in order to arouse their interest.

Fluidization *(in-class demonstration)*

Fluidization can be demonstrated in the classroom using a small bed connected to a portable compressor, or if the bed is small enough, a willing volunteer's lungs.[7] Behavior that can be displayed includes the way the fluidized bed remains level as the bed is tilted and the floating and sinking of objects of different density when the bed is fluidized. This can be contrasted with the behavior of these objects in the bed when it is vertically vibrated (see Vibrational segregation above).

Bubbling behavior can be demonstrated by filling a long tube most of its length with a Geldart Group A powder. Inverting the tube will result in a slug slowly rising up the length of the column.[6] Again, students could be asked beforehand to predict what will happen when the tube of fine powder is inverted. Many may expect the powder to move as a solid plug from one end to the other.

Flow Improvement Due to Powder Agglomeration
(in-class demonstration)

The dramatic improvement in the flow properties of granulated versus ungranulated materials can be demonstrated by setting two hoppers side-by-side, one with the raw fine powder and the other with the same powder after it has been granulated. When inverted, the raw powder arches and does not flow without tapping, whereas the granulated product flows freely (see Figure 4). Small batches of granules for use in this demonstration can easily be prepared at home in a domestic food processor.

Figure 4. *Granulated powder (left-hand side) flows easily into lower hopper, whereas raw powder arches and does not flow (right-hand side).*

OTHER RESOURCES FOR POWDER TECHNOLOGY EDUCATION

If you do not have the resources or time to build and perform these demonstrations, many of them are shown as video clips on a CD produced by Rhodes and Zakhari.[8] An expanded version of this CD is due out soon that will include interactive problems.

The Particle Technology Forum of the American Institute of Chemical Engineers has established a website with many good educational resources for particle technology.[26] For ideas on how to construct and structure an introductory course on powder technology, we suggest reading the papers by Chase and Jacob[3] and Donnelly and Rajagopalan,[4] and also the textbook by Rhodes[23] that was written specifically with the purpose of being an introductory undergraduate textbook.

CONCLUSIONS

Instructors of powder technology courses have no excuse for not using visual, hands-on demonstrations to introduce a little more variety and interest to their teaching. Most of the demonstrations mentioned in this paper can be built at little cost using materials readily available in most engineering departments. No expensive or hazardous chemicals are needed, and most of the powders can be found at your local beach or supermarket. Asking students to guess the powder behavior before the demonstration is performed is an effective tool for engaging their interest.

REFERENCES

1. Felder, R., “How About a Quick One?” *Chem. Eng. Ed.,* **26**(1), 18 (1992)
2. McKeachie, W. J., *Teaching Tips,* 8th ed., D.C. Heath & Co., Lexington, MA (1986)
3. Chase, G.C., and K. Jacob, “Undergraduate Teaching in Solids Processing and Particle Technology: An Academic/Industrial Approach,” *Chem. Eng. Ed.,* **32**, 118 (1998)
4. Donnelly, A.E., and R. Rajagopalan, “Particle Science and Technology: Educational Initiatives at the University of Florida,” *Chem. Eng. Ed.,* **32** 122 (1998)
5. Fan, L.-S., “Particle Dynamics in Fluidization and Fluid-Particle Systems: Part 1. Educational Issues,” *Chem. Eng. Ed.,* **34**, 40 (2000)
6. Fan, L.-S., “Particle Dynamics in Fluidization and Fluid-Particle Systems: Part 2. Teaching Examples,” *Chem. Eng. Ed.,* **34**, 128 (2000)
7. Klinzing, G., “Experiments, Demonstrations, Software Packages and Videos for Pneumatic Transport and Solid Processing Studies,” *Chem. Eng. Ed.,* **32**, 114 (1998)
8. Rhodes, M., and A. Zakhari, “Laboratory Demonstrations in Particle Technology,” CD, Monash University, Melbourne, Australia (1999)
9. Idea introduced to the authors by Professor Nafis Ahmed, formerly of the University of Newcastle, Australia (1998)
10. Idea introduced to the authors by Professor Kevin Galvin, University of Newcastle, Australia (1998)
11. Pashias, N., and D.V. Boger, “A Fifty-Cent Rheometer for Yield Stress Measurement,” *J. Rheol.,* **40,** 1179 (1996)
12. Shaw, D.J., *Introduction to Colloid and Surface Chemistry,* 4th ed., Butterworth Heinemann (1992)
13. Hunter, R.J., *Introduction to Modern Colloid Science,* Oxford Science Publications (1992)
14. Johnson, S.B., G.V. Franks, P.J. Scales, D.V. Bogher, and T.W. Healy, “Surface-Chemistry-Rheology Relationships in Concentrated Mineral Suspensions,” *Int. J. Miner. Process.,* **58**, 267 (2000)
15. Hapgood, K.P., J.D. Litster, S.T. Biggs, and T. Howes, “Drop Penetration into Porous Powder Beds,” *J. Colloid & Interface Sci.,* **253**, 353 (2002)
16. Idea introduced to the authors by Dr. Bryan Ennis and Professor Jim Litster during one of their industrial short courses on granulation (1999)
17. Ennis, B.J., G.I. Tardos, and R. Pfeffer, “A Micro-Level Based Characterization of Granulation Phenomena,” *Powder Technol.,* **65**, 257 (1991)
18. Liu, L.X., S.M. Iveson, J.D. Litster, and B.J. Ennis, “Coalescence of Deformable Granules in Wet Granulation Processes,” *AIChE J.,* **46**, 529 (2000)
19. Jenike & Johansen, Westford, Massachusetts
20. Idea mentioned to the authors by Professor Martin Rhodes, Monash University, Australia (2000)
21. Reynolds, O., “Experiments Showing Dilatancy, a Property of Granular Materials, Possibly Connected with Gravitation,” *Proc. Roy. Inst.,* **11**, 354 (1886)
22. Nagel, S., “Shifting Sands,” *New Scientist,* 53, July (2000)
23. Rhodes, M., *Introduction to Particle Technology,”* Wiley (2000)
24. Liffman, K., D. Gutteridge, M.J. Rhodes, and G. Metcalfe, “The Brazil Nut Effect,” CHEMECA ‘98, Paper #122
25. Shinbrot, T., and F.J. Muzzio, “Non-Equilibrium Patterns in Granular Mixing and Segregation,” *Physics Today,* **53**, 25, March (2000)
26. <http://www.erpt.org/> ❐