PARTICLE TECHNOLOGY CONCENTRATION AT NJIT

An NSF-CRCD Program

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Particle technology is concerned with the characterization, production, modification, flow, handling, and utilization of granular solids or powders, both dry and in slurries. The technology spans a host of industries, including chemical, agricultural, food products, pharmaceuticals, ceramics, mineral processing, advanced materials, munitions, aerospace, energy, and pollution control. A need for incorporating the subject into the undergraduate and graduate engineering curriculum has been well recognized.[1,2]

As a consequence of an NSF Combined Research and Curriculum Development (CRCD) grant, an interdisciplinary concentration of new courses in particle technology is now being developed at the New Jersey Institute of Technology (NJIT) by faculty members in several of its departments. The concentration consists of three principal courses: 1) "Introduction to Particle Technology," designed for upper-level undergraduates and first-year graduate students; 2) "Current Research in Particle Technology," intended for graduate students; and 3) "Experiments and Simulations in Particle Technology," intended for upper-level undergraduates and first-year graduate students. It is believed that these new courses cover material that is substantially absent in established engineering curricula.

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Anthony D. Rosato *is Associate Professor of Mechanical Engineering at NJIT and is director of the Particle Technology Center. His research interests are in computer-simulated modeling and experiments on rapid flows of granular materials and in curriculum development in particle technology.*

There are many challenges in developing this curriculum, many of them due to the fact that the scope of particle technology is so broad-based and interdisciplinary. The primary objective of an NSF-CRCD award is to bring the current research of the PIs and other researchers in the field into the curriculum. But since the subject of particle technology is so broad and diverse, it soon became apparent to the PIs that the students required a large amount of background material before the research material could be taught effectively. To meet this challenge, the introductory course was designed to contain such background material. It was also clear that one individual may not have the necessary expertise required to develop a comprehensive program of education or, in some cases, even a single course. Thus, a team of instructors was needed to develop the curriculum concentration, and the two advanced courses were staffed with more than a single instructor.

Another major challenge was to establish particle technology as an interdisciplinary academic concentration that was integrated into the engineering curriculum without adding extra credits or dropping existing requirements. This was met by introducing the three courses in such a way that a student could take one or more of them as an undergraduate elective. Moreover, while the first course provided the necessary background material, the other two courses were designed so that an undergraduate student with good academic standing or a graduate student could take them without having taken the first course. In addition, several key experimental modules from the laboratory course were incorporated into the core undergraduate laboratory courses so that every graduating engineer from either the chemical or the mechanical engineering department was exposed to some aspects of particle technology.

Yet another challenge in this curriculum development was to present the basic concepts, industrial practice, and new research in particle technology without overwhelming the students, while at the same time exposing them to a new set of analytical and experimental tools required for problem solving. This challenge is being met, in part, by the development of an instructional laboratory and the development of user-friendly computer simulations so that the students (and the instructor) have access to these facilities that enhance the classroom instruction. Further difficulties arose due to the fact that it was necessary to employ equipment and software that are not routinely used in the current engineering curriculum, such as state-of-the-art instrumentation for characterization, mixing, and flow property measurement, as well as image analysis, computer simulations, and video animation systems. In addition, students must also be taught the use of associated software. Since the current curriculum does not have the infrastructure to accommodate this, our challenge was to develop an easy-to-use set of instructions and to train graduate students who would be available to help the students taking the courses. Thus, providing the proper background material for the wide variety of topics has been more demanding than delivering the material related to the PIs' research.

COURSE DESCRIPTIONS

COURSE 1
Introduction to Particle Technology

As previously discussed, this course is intended to provide background material in particle technology. Since the material covered in this class is not available in a single book, several reference books were used.[3-5] The course covers a variety of topics in particle technology, described below.

Particle Characterization • Determination of the shape and size of particles, sampling, shape factors, and fractal dimensions for irregular shapes, Stokes' law/sedimentation, electrozone sensing techniques (Coulter Counter), radiation scattering methods (Malvern Mastersizer), optical size-measurement systems.

Coulomb Materials • Mechanics of Coulomb materials, yield criterion of granular materials, active and passive Rankine failure states, unconfined yield stress, angle of repose and internal friction angle, Coulomb's method of wedges, Janssen's equation for stresses on walls of bins and hoppers, Walter's switch stress.

Hopper Design • Core flow versus mass flow, Jenike shear cell and yield locus, material flow function and flow factor to size hopper outlet and slope, consolidation and compaction effects during loading and unloading hoppers.

Conveyor Belts • Design based on handbook by manufacturer trade associations, conveyability characteristics, angle of repose, angle of surcharge, flowability, density, dustiness, wetness, abrasiveness, corrosiveness and temperature, power requirements, belt tension, and idler spacing.

Solid-Gas Separation • Aero-mechanical separators, wet scrubbers, electrostatic precipitators and filters, pressure drop, flow rate, grade efficiency and cut size to characterize devices, cyclone dry-separation.

Gas Fluidization • Purpose of fluidized bed, aeratable, sand-like, cohesive, and spoutable powders, bed pressure drop, minimum fluidization velocity, slugging, bed expansion, entrainment of solids in exhaust, and heat and mass transfer.

Suspensions and Sedimentation • Stokes' flow, Faxen's law, hydrodynamic interactions, corrections to Stokes' law, "effective fluid" model of a suspension, effective velocity, Einstein viscosity, sedimentation speed in a dilute suspension.

Slurries and Suspensions • Forces on a particle in a fluid, terminal settling velocity, drag coefficient, Archimedes' number, homogeneous suspensions rheological behavior, measurement devices, Newtonian, power-law, Bingham plastic and Casson constitutive equations, Arrhenius equation, temperature-reference method, laminar and turbulent flows of suspensions in pipes, mixing of powder in agitated tanks, saltation, Durrand's correlation, vessel agitation, critical speed of an agitation impeller.

Particle Size Enlargement • Industrial applications, agglomeration methods, mechanics of agglomeration, inclined-disk agglomerators, fluidized bed, and drum granulators.

Particle Size Reduction • Crushing and grinding, forces in size reduction, Rittinger, Kick, Bond, and Holmes methods for energy requirements, mathematics of predicting product size distribution, description of crushing and grinding machines in industry, example of size distribution in hammer mill.

Collision Mechanics • Coefficient of restitution, planar impact of spheres, normal collision of elastic spheres, collision of frictional elastic spheres, collision of inelastic spheres.

COURSE 2
Current Research in Particle Technology

This course, intended for graduate students (but may also be taken by upper-level undergraduates with good academic standing), is theoretical in nature and emphasizes micro-level modeling for the understanding of macroscopic behavior. It includes mathematical modeling and computer simulations. Also incorporated into the course are recent research developments in the field that do not yet appear in standard textbooks.

The course requires team teaching and also uses guest lecturers. While the course content may change depending upon the instructor, the main topics include: contact/collision mechanics, including hard sphere and soft sphere contact modeling; computer simulations for dry granular flows, including stochastic, geometric, and dynamic simulations; computation of transport properties; modeling of granular flows; dynamics of small numbers of sedimenting particles; effective viscosity of a suspension; sedimentation speed in a suspension; modeling of granular and fibrous bed filtration and fluidized beds. Many of these topics involve examples taken from the research of the PIs. The course also requires development of computer simulation codes by the students.

Several guest lecturers from outside have already contributed to this course: Dr. P. Singh (Processing of Complex Fluids) from Los Alamos Laboratory; Dr. L.-S. Fan (Fluidization Engineering) from Ohio State University; Dr. O.R. Walton (Discrete Element Simulations of Granular Flows) from Lawrence Livermore Laboratory; Dr. C. Wassgren (Experiments and Simulations of Vibrated Beds) from CalTech; Dr. K. Leschonski (Particle Classification) from CUTEC, Germany; and Dr. A. Caprihan (Nuclear Magnetic Resonance Imaging of Highly Energetic Flows) from The Lovelace Institutes, New Mexico.

COURSE 3
Experiments and Simulations in Particle Technology

As part of the NSF-CRCD grant, a new combined research and instruction laboratory is being developed, containing a variety of experimental equipment that includes instructional as well as research equipment. The laboratory is still under development, and several new experimental modules are currently undergoing construction. The completed modules are:

❑ ***Angle of Repose*** The students are asked to measure the angle of repose of a variety of granular materials using four different classical methods (fixed-height table, fixed-base cone, tilting table, and rotating cylinder). A digital camera and image analysis are used to measure the angle of repose from the four methods and results are compared.

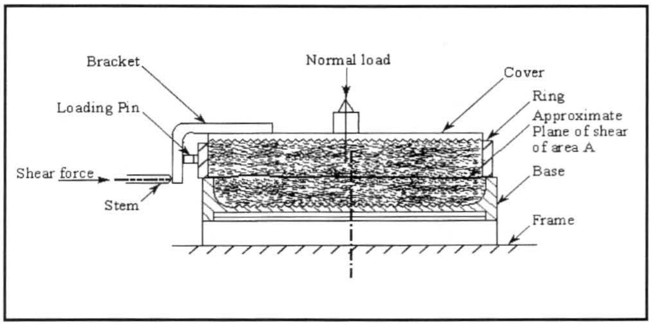
❑ ***Particle-Size Analysis Using Sieves*** Sieving, one of the simplest, oldest, and most inexpensive methods of determining particle size distribution, which is widely used in industry,[6] is effective for sizes down to about 38 microns. The sieving apparatus used in our experiments is an Octagon 2000 Vibrated Siever with a set of sieves ranging from 25 microns (mesh #500) to 4.0 mm (mesh #5). The students analyze samples of coarse sand to obtain a size-distribution curve as well as the cumulative-distribution curve by weighing the residuals at each sieve. For the tested samples, the students also collect data to study the sieving rate.

❑ ***Particle-Size Analysis Using Laser Diffraction Technique*** The students perform size analysis of samples obtained through a grinding experiment using a Malvern Mastersizer X Laser Diffraction particle-size analyzer. The samples analyzed had a size range from a few microns to about 100 microns. During the course of the experiment, the students learn about sample collection, preparation, and the use of the Mastersizer. The most basic task of sample collection is perhaps the most difficult, and we realized that a better sampling scheme would be required. The Mastersizer software allows for selecting different scattering theories and refractive index models. Students use both Fraunhofer and Mie scattering theories and also have the flexibility of changing the model used for the refractive index. For each case, the results such as the "mode" (of the size distribution) and the "residual" (of the fit of measured and computed scattering data for all the detectors) are recorded.

❑ ***Size Reduction/Grinding with a Ball Mill*** For the basic ball-mill experiment, a ball mill (Paul Abbe) with a ceramic cylindrical jar and cylindrical Burundum Alumina as the grinding media is used. The students are asked to perform a simple grinding experiment to study the rate of change in the particle size distribution as a function of time. A challenge in this experiment is to find a suitable test material capable of demonstrating the main features of the grinding process within a 2- to 3-hour lab period. For the sake of demonstration, soft gravel-like material of size 250 microns to about 4 mm is utilized.

Students are asked to analyze the results for the time dependence of size distribution, power consumption, and specific surface area.[4]

❑ ***Material Testing by Jenike Shear Cell for Design of Mass Flow Hoppers*** The purpose of this experiment is to calculate parameters of a mass-flow hopper for a given test material. The main issue in hopper design is the material testing procedure that provides information about flowability and cohesiveness of the material needed to select the hopper slope and minimum outlet size. There are many different methods to test the flowability of the material,[7] although the Jenike method[8] (which gives the Jenike yield locus) is still considered the most reliable and is perhaps the most widely used technique in industry. There is a detailed standard procedure[9] for using the Jenike apparatus (see Figure 1), as the variability and the scatter in the test data is found to be very wide if careful testing is not performed. Each yield locus is formed by plotting the normal stress (loading weight) versus the prorated shear stress for at least three operating points. For each operating point on the curve, the material must be pre-consolidated by the consolidating weight (see Figure 2), and then the shear test must be performed for a



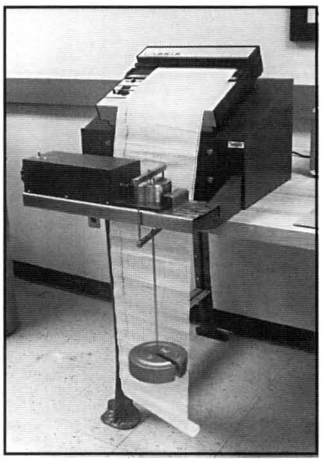


Figure 1.

Jenike shear tester: Schematic above and photograph at left.

chosen loading weight (Figure 1), so that the loading weight is less than or equal to the consolidating weight. Students test materials such as flour, powdered sugar, and cornstarch. Highly cohesive materials (*e.g.*, cornstarch) pose difficulties in obtaining reliable results. We found that the test apparatus was not very user friendly, and the task of complete testing is tedious, generally requiring 5 to 6 hours.

❑ ***Study of Rise of a Single Large Sphere in a Vibrated Granular Bed*** Size segregation is often an undesirable outcome of handling and/or processing operations of bulk solids. In general, a large ball placed at the bottom of a vibrated bed will rise to the surface.[10] In the laboratory sessions, the students examine various behavioral regimes of the vibrated bed and make observations of the rise time of the large particle at different operating conditions.

❑ ***Dilatometer Measurement of the Minimum Sintering Temperature of Fluidized Solids*** Many of the processes using fluidized beds operate at high temperatures, which cause softening and/or partial melting (sintering) of the solids' surfaces, thereby requiring higher gas velocities to keep the bed in the fluidized state. The purpose of this experiment is to measure the minimum sintering temperature T_s (the temperature at which thermally induced surface softening and sintering begins), an intrinsic property of the solid-particle surface. A relatively simple procedure to estimate T_s makes use of constant-rate dilatometry[11-13] to obtain the elongation-contraction versus temperature curve for a porous rod composed of the granular material in question (see Figure 3). In the experiment, a Theta Industries-Econo I dilatometer is used to heat a small sample of powder (about 1.2 grams) at a constant rate (maximum is 15°C/minute) to temperatures as high as 1600°C. Students set up and program the dilatometer to operate overnight at a constant heat-

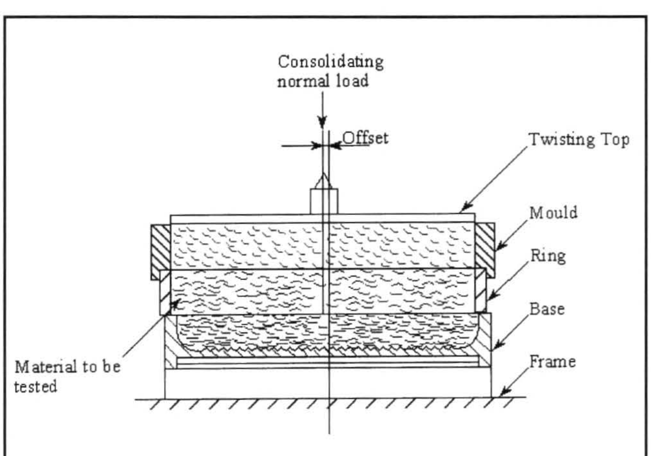


Figure 2. *Material being pre-consolidated for Jenike shear test.*

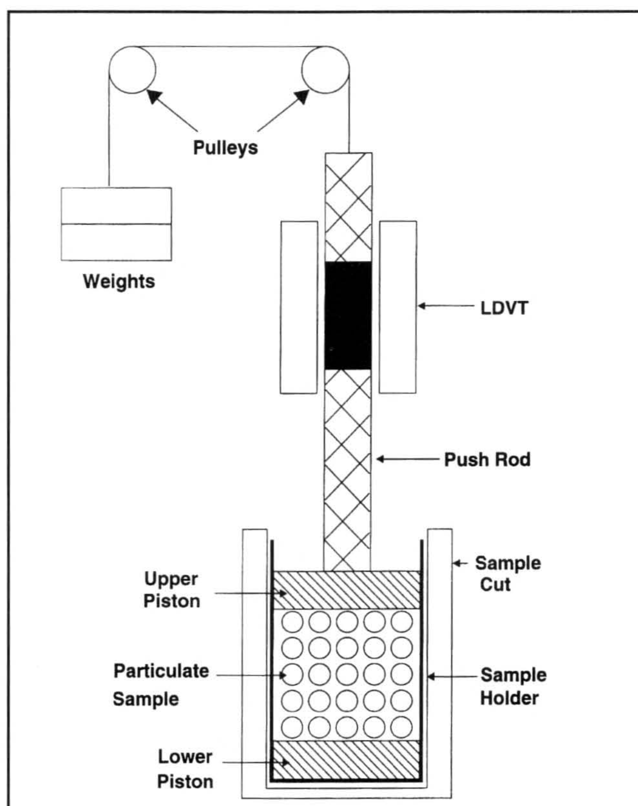


Figure 3. *Schematic diagram of a dilatometer used for measuring minimum sintering temperature of powders.*

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ing rate using alumina powder in a Nitrogen atmosphere. Results are analyzed the next day to determine T_s.

❑ ***Particle Sedimentation*** The falling-ball viscometer is the first in a sequence of experiments concerning suspensions and sedimentation. The apparatus consists of a glass cylinder (100 cm long by 10 cm diameter) containing a viscous fluid (UCON fluid 50-HB-3520, manufactured by Union Carbide), as shown in Figure 4. Small numbers of particles placed in the fluid at the top of the cylinder may be observed as they sediment along the axis of the cylinder. Students receive instruction on the basic theory of sedimentation at low Reynolds number and its application to size segregation and characterization. Using the manufacturer's specifications of the physical properties of the fluid, a collection of particles, a balance, a thermocouple, a meter stick, and a stop watch, students are asked to investigate some of the physical characteristics of the system. Hydrodynamic properties investigated include particle-wall and particle-particle interactions, inertial effects, and thermal effects. Particular emphasis is placed on having students explain variability in observations. Reports are kept on file and future students will be asked to analyze their data and to reconcile their results with those of groups from previous years.

❑ ***Other Planned Experiments*** Other experiments will be selected from: blending and mixing; segregation in poly-disperse vibrated beds; conventional fluidized bed; rotating fluidized bed; core-flow/mass-flow hoppers; particle-collision properties; non-intrusive tracking in granular flows; dry particle coating; simulation and visualization of granular flows.

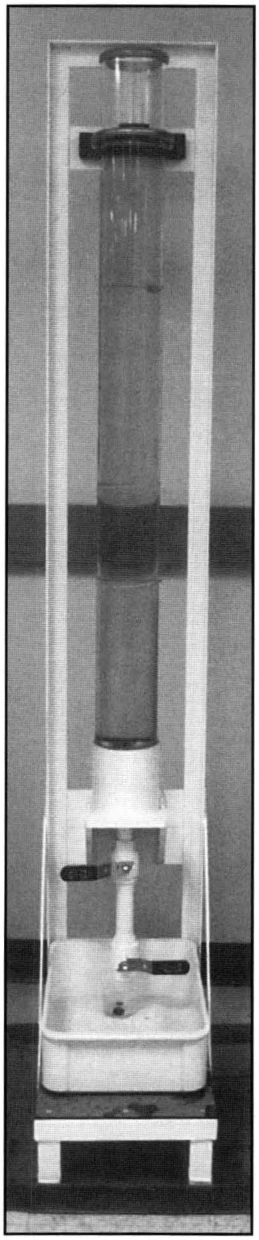

Figure 4. *Photograph of the sedimentation column, filled with UCON fluid.*

SPECIAL COURSES

As a part of curriculum development, two special courses were also given: "Fluid-Particle Flows at Low Reynolds Number" (offered as Special Topics in Applied Mathematics by Prof. J. Luke) and "Image Analysis for Applications in Particle Technology" (by Prof. R. Dave). These courses had the objective of "trying out" part of the material that would eventually be included in the new three-course particle technology concentration.

ACCOMPLISHMENTS

Some of our major accomplishments are:

• Formation of an Advisory Board with particle technology experts from industry and academia. The board comprises representatives from 12 industrial companies and 6 universities. Board meetings have been held every March, beginning in 1995.

• Development of and offering the introductory course, "Introduction to Particle Technology," in the fall of 1995 and the fall of 1997 by Dr. I. Fischer. Approximately 20 students, both undergraduates and graduates, were enrolled each semester.

• Offering of the graduate course "Current Research in Particle Technology" by Dr. R. Dave during the spring of 1996 and by Dr. A. Rosato during the spring of 1997. Approximately ten students were enrolled each time.

• Offering of two special courses

• Designing and building the new combined research and instruction laboratory.

• Offering of the laboratory course "Experiments and Simulations in Particle Technology" in the fall of 1996 and again in the spring of 1998 by Dr. R. Dave.

SYNERGY OF EDUCATION AND RESEARCH PARTNERSHIPS

During the course of this project, we recognized that a number of partnerships were required for a successful completion. The first step toward developing these partnerships was through the Advisory Board (AB), which has been of significant help in providing guidance and advice as well as technical and financial support. As an example, four guest speakers, two of whom are members of our AB, delivered three-hour lectures to the students in the graduate course. Also, one industrial member of the AB presented a lecture on particle-size-analysis techniques in the laboratory course, and another representative from a member company spent a full day with our students on the Jenike shear testing experiment. Our partnerships also include collaborations with a number of universities, including the NSF-ERC in Particle Science and Technology at the University of Florida.

While research activities in the area of particle technology have been ongoing for several years at NJIT, the CRCD award has served as the impetus for developing a number of new research collaborations as well as the formation of the Particle Technology Center at NJIT. Readers can access its web site at

http://www-ec.njit.edu/ec_info/image2/ptc

Moreover, our efforts have been recognized at NSF (we were asked to showcase our CRCD program as part of the exhibition held at the 1996 annual ASEE meeting at Washington, DC), by other academicians, by recognized experts from industry, and most recently by the State of New Jersey. The first and fourth authors received one of the new R&D Excellence Awards from the state of New Jersey to establish a Particle Processing Research Center in collaboration with Rutgers University. Readers can access its web site at

http://www-ec.njit.edu/ec_info/image2/PPRC/

This program provides seed money ($300,000/year) for five years to establish a long-term, self-supporting program with a focus on basic science with industrial relevance, having intermediate and long-term commercialization potential. In summary, our experience in forging partnerships has proven very beneficial and we believe that even more can be gained from these partnerships in the future. The synergism between research and education is obvious, and the success of both depends heavily on partnerships.

CONCLUSIONS

The development of a curriculum concentration in particle technology is ongoing and our experience has been quite positive so far. Despite challenges due to the broad and interdisciplinary nature of the subject material, we have made substantial progress. All three of the new courses have already been offered twice. In the near future, we will focus on dissemination of the materials that we have developed. Currently, our goal is to put sample notes and examples on our web sites and to provide several modules from each course to colleagues for use at other universities. We will also share information on our laboratory development, simulation codes, and video animations.

The course material presently focuses more on the "mechanical" aspects of particle technology as compared to the "chemical" aspects. This is in part due to the fact that three of the five team members are from the Mechanical Engineering Department and have served as principal instructors of the courses offered so far. Current efforts are to make the material more balanced and include chemical reactors involving particles, mechano-chemistry, and suspension rheology so as to attract more students from chemical engineering and other engineering disciplines. In the next few months, several experimental modules will be incorporated into the core undergraduate laboratory courses, and the results of that experience will be reported in the future.

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