

PARTICLE TECHNOLOGY IN THE ENGINEERING CURRICULUM AT NJIT

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Abstract

This paper discusses the development of a three-course concentration in particle technology at NJIT offered across the engineering curriculum which addresses the urgent need for undergraduate and graduate education in this vital field of manufacturing. Funded by an NSF-CRCD grant, a major goal is to integrate recent particle technology research conducted at NJIT and by researchers at other institutions into the three-course sequence. This educational initiative also address one of the main focus areas of NJIT's recently formed Particle Technology Center (PTC), which is comprised of an interdisciplinary group of faculty from the Departments of Mathematics, Mechanical, Chemical, Civil and Electrical Engineering, as well as visiting scholars, post-docs and graduate and undergraduate students. The first course, entitled "Introduction to Particle Technology" which is intended for upper-level undergraduates and first-year graduate students, was given in the Fall 1995 semester and a detailed description of the topics covered is provided. This is followed by a summary of an additional course ("Image Analysis Applications in Particle Technology") also given in Fall 1995, specifically created to familiarize graduate students with some of the special experimental facilities and analytical tools available in the PTC. An upper-level graduate course, entitled "Special Topics in Applied Mathematics: Particle Technology," and offered in the summer 1995 through the Mathematics Department is also described. This course, although not specifically a part of the CRCD project, contributed to the implementation of the program through the development of course materials in modeling fluid-particle flows at low Reynolds numbers.

Introduction

Particle technology is concerned with the characterization, production, modification, flow, handling and utilization of granular solids or powders, both dry and in slurries. This technology spans a host of industries including chemical, agricultural, food products, pharmaceuticals, ceramics, mineral processing, advanced materials, munitions, aerospace, energy and pollution. Recently, the US Department of Commerce reported that particulate products generate one trillion dollars annually to the US economy. For example, E.I. du Pont de Nemours & Co. estimated that of the 3,000 products that it sold, 62% were powders, crystalline solids, granules, flakes, dispersions, slurries and pastes. A further 18% of the products incorporate particles to impart key end-use properties. In the chemical process industries, a minimum estimate of 40% or \$61 billion of the value added by the chemical industry is linked to particle technology. Therefore the chances of our graduating engineers encountering problems related to particle technology in their future careers are very high, and it is important for them to be exposed to this subject during their education.

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 created at the New Jersey



Institute of Technology by professors in several of its departments. It is believed that these courses cover material which is substantially absent in the established engineering curricula. In this paper, ongoing efforts towards this curriculum development are described.

Engineering Graduates Need to Know About Particle Technology

Particle technology is concerned with solid materials handled as a mass of small, individual elements. Matter in such form is often referred to as bulk, granular or particulate material. This form of solid material often appears to flow like a liquid and that infers that particle mechanics can be handled by the methodologies which have been developed for analyzing the behavior of fluids.

In actual practice, however, designing equipment and facilities to handle bulk solids on the basis of fluid mechanics can lead the engineer astray. As an example, consider the ubiquitous storage/flow hopper. It is typical to assume that the pressure exerted on the walls of a storage hopper in which it is stored can be predicted using the laws of hydrostatics appropriate for liquid in a tank. However, a liquid is substantially different than a bulk solid. In a liquid the shear stress is proportional to the rate of strain. As Coulomb observed, in a bulk solid the shear stress is proportional to the normal stress. This also means that the laws of solid mechanics, where shear stress is proportional to the amount of deformation, cannot be applied. Thus, if a designer models granular material as a fluid, it will be concluded that the normal load on the wall of a storage hopper increases linearly with depth. The actual load is better modeled by Janssen's equation (see [1]) which predicts that the normal stress on the bunker wall increases exponentially to an asymptotic value. If a designer were tempted to optimize the storage hopper design by tapering the thickness of the wall toward the top, the hydrostatic model would result in overbuilding at the bottom and perhaps underestimating the thickness at the top. The hydrostatic model also fails to predict the shear stress which a granular material at rest in a bunker exerts on the wall, and neglecting that load may result in a failure of the structure.

The fluid-mechanics hydrostatic model also is inadequate for dealing with the mechanics of emptying a supply hopper. Hydrostatics gives no insight as to what the slope of the hopper should be or about the size of the outlet. If the hopper slope is too shallow, only that material immediately above the outlet will flow, the remaining material residing in the bunker will become unusable and possibly deteriorate with time. Also, the outlet can clog, forming an arch-like dome of material above it within the hopper. Typical industrial practice when confronted with this predicament is to whack the hopper with a sledge hammer to provide a shock which will initiate flow. While the results may be satisfactory, very often instead of no flow there is a condition of excessive flow called flooding. In that situation the discharge through the outlet becomes uncontrollable, usually resulting in spillage sometimes to the extent of workmen being buried. Such unsatisfactory design of bins and hoppers has resulted in part, from engineering graduates being unfamiliar with methods developed for considering the handling of particulate materials such as the Jenike methodology for selecting hopper slope and outlet size and the Walters switch-stress analysis for predicting pressure excursions which occur in a bin being emptied.

The mechanical engineering and chemical engineering curricula in this country have virtually nothing to guide their graduates in considering these and other matters dealing with the handling of granular solids. The soil mechanics in civil engineering is helpful but limited. Moreover, the main objective in soil mechanics is the prevention of flow of the granular material. This in contrast to the main objective in particle technology where initiation and continuation of flow are more important. Consequently it was proposed to create a concentration of three courses to introduce particle technology into the engineering curriculum



New Courses in Particle Technology Offered at NJIT

As part of the NSF-CRCD project, three new courses are being developed at the New Jersey Institute of Technology. The first of these courses is oriented toward the undergraduate students and consists of a general survey of particle technology which provides a good theoretical basis, but also features coverage of such applications as the students are likely to encounter when they have graduated and have entered industry. A second course is intended for graduate students and is oriented more towards theoretical aspects, including mathematical modeling and computer simulations which can predict bulk behavior of particulate flows from the properties of the material. This course also presents recent research developments in the field not yet appearing in standard textbooks. The third course will take place in the laboratory where students will gain hands-on experience with the behavior of granular materials using model experiments as well as realistic solids processing equipment. Some of the laboratory experiments will eventually be incorporated into both chemical and mechanical engineering required laboratory courses so that all of these students will receive at least some exposure to particle technology.

A major challenge of the NSF-CRCD project is to present the basic concepts, industrial practice and new research in particle technology without overwhelming the student, yet exposing him/her with a whole new set of tools required for problem solving in this field. This will be done through classroom instruction, physical experiments as well as computer simulated experiments. Our syllabus, which is very ambitious, makes the task of delivery of education very difficult and thus creates a challenge for which we are preparing ourselves and our graduate students, who will, in turn, help the students in the physical and computer laboratories. The difficulties arise due to the fact that we plan to use equipment and software which are not routinely used in the current engineering curriculum. These include not only state-of-the-art particle instrumentation for characterization, mixing and flow property measurement, but also image analysis and video animation equipment. We must also teach the students the use of associated software. The current curriculum does not have the infrastructure to accommodate this, and our challenge is to develop an easy to use set of instructions, and to have trained graduate students available for consultation.

Consequently, two additional special courses consisting of both physical experiments and computer simulations concerned with particle technology have been developed and already offered. The first special course, entitled "Image Analysis Applications in Particle Technology", was offered by Dr. R. Dave of Mechanical Engineering Department, in Fall 1995. The intention was to train our graduate assistants and other students so that they will be able to make significant technical contributions towards the development of the laboratory course to be offered in Fall 1996. It is expected that the students completing this course can easily utilize image analysis hardware and software to help automate data collection and analysis for a variety of particle technology experiments. For example, experimental measurement of angle of repose in a rotating drum or experimental measurement of pre- and post- collisional velocities to determine coefficient of restitution of a sphere. The second special course entitled, "Special Topics in Applied Mathematics: Particle Technology" was offered by Dr. Jonathan Luke of the Mathematics Department in the summer of 1995. The objective behind this course was to build an infrastructure of knowledge in this area among graduate students of applied mathematics.

To help us in preparation, evaluation and dissemination of the course material, an advisory board consisting of practicing engineers in industry, academics from both US and abroad, and government-laboratory scientists was formed. It comprises representatives from 9 industrial companies, 5 universities and a US National Laboratory. It is anticipated that their help in finalizing the course contents and methods of delivery will be invaluable.



Also related to this educational thrust is the establishment of a Particle Technology Center at the New Jersey Institute of Technology which will foster research, education, training and technology transfer in particle technology.

In the following sub-sections, several of the new courses which have already been offered are described. The new courses which are currently being developed for future presentation will be described in a forthcoming paper.

The Undergraduate Lecture Course

During the Fall 1996 semester, Dr. Ian S. Fischer conducted an undergraduate lecture course "Introduction to Particle Technology" for twenty students majoring in mechanical or chemical engineering and representing a variety of intellectual, ethnic and gender backgrounds. Below is a description of the topics covered in this course; for more details, see [1-4].

Particle Characterization

A lecture on particle characterization discussed techniques for determining the shape and size of particles as well as methods of taking size samples to obtain representative distribution. The terminology for describing particle shape was presented, including the use of Fourier-series coefficients and fractal dimensions to quantify the irregular shapes characteristic of particles. Various physical devices for obtaining size and size distribution of particles were explained, including sedimentation techniques based on Stoke's law, Coulter counter technique, radiation scattering methods and a review of optical size-measurement systems.

Coulomb Materials

A series of lectures developed the mechanics of Coulomb materials, those where the shear stress is directly proportional to the normal stress. These materials behave significantly different than an elastic solid where stress is proportional to strain or a liquid where stress is proportional to the rate of strain.

The first matter considered was the concept of Mohr's circle, used extensively throughout the lectures. While this has been covered in previous mechanical engineering courses, the review was helpful and more importantly, it was a new concept for the several chemical engineers taking the course.

The concept of the Coulomb yield criterion, defining the failure of a granular material, was introduced along with the coefficient of friction, angle of friction and the coefficient of cohesion. It was shown how the yield line based on the Coulomb criterion places a limit on the size of the Mohr's circle representing the state of stress at a point in a particulate material. Consequently the student is shown how to evaluate the amount of loading which will cause the failure, hence the flow, of a bulk solid.

The active and passive Rankine states, developed for civil-engineering soil-mechanics applications, was applied to the handling of particulate solids. It was shown that below a certain critical depth a cohesive granular solid is in compression while above that depth it is in tension and cracks may develop. The lectures noted that at the top surface of a particulate material there is a horizontal compressive stress called the unconfined yield stress.

The angle of repose of a granular material was considered, and it was shown how classical analysis has found it equal to the angle of friction if the material is cohesionless. Expressions for the angle of repose were also developed for cohesive materials and it was shown how the angle of repose varies with the height of a pile.



The expression for the maximum height of vertical wall of a cohesive material was also derived. The concept of the “fully rough wall” and the matters of failure within a bulk material versus failure between the material and the wall of its container were discussed.

Coulomb’s method of wedges was detailed. The case of active failure was developed for both fully rough and partially-rough walls. The passive-failure case was also analyzed for the students, and the effect of inclined walls and top surfaces was shown. The accuracy of Coulomb’s method of wedges was discussed along with Reimbert’s approximations.

The presentation of Janssen’s equation for the stresses on the walls of bins and hoppers began by discussing the assumptions involved. It was shown how Janssen considered the static equilibrium of differential horizontal slices of material and obtained equations which predict that the wall stresses increase exponentially to asymptotic values. It is emphasized how this is very different than the linear increase which a liquid exerts on the walls of a tank. The influence of a surcharge (a load on top of the granular material in the bunker) is also noted, i.e., its effect becomes negligible with increasing depth. Janssen’s equation is modified to deal with non-circular cross-section bunkers, and the concept of hydraulic mean diameter is introduced. Equations are developed for the stresses induced by inclined top surfaces and the stresses in conical and wedge-shaped hoppers comprising the bottoms of bins. Walter’s switch stress, a method of roughly predicting the pressure pulses which occur in the walls of a bin being emptied was presented. In addition to the analysis, the students were alerted to certain practical matters of bunker and hopper design, including thermal racking and the moisture-induced expansion of materials in storage.

Hopper Design

These lectures addressed the matter of hopper design, and contrasted core-flow with mass-flow hoppers. In core-flow hoppers, only that material generally above the outlet will move when the outlet has been opened. Core-flow hoppers are particularly susceptible to clogged outlets, flooding and pulsation in flow rate and bulk density. In the mass-flow hopper, all of the material moves out of the opened outlet, thereby avoiding clogging, retention of material and the other problems associated with the core-flow behavior. Having discussed these matters, procedures for hopper design are then presented to the students.

The Jenike shear cell is described and it is shown how data obtained from its use results in the Jenike yield locus. The stresses in an arch of material comprising an outlet clog are considered and the unconfined yield stress, material flow function, flow factor and critical applied stress are introduced. The students are then shown how to use this information with the Jenike flow-factor charts to size a hopper outlet and determine the slope of the hopper walls. The methodology is presented for both circular and rectangular cross-section hoppers. The matters of time consolidation of material and the compaction effects occurring when hoppers are loaded and unloaded are mentioned to complete the discussions about hopper design.

Conveyor Belts

The lectures about the design of conveyor belts is based largely on a handbook produced by a manufacturers trade association [4], and is similar in methodology to procedures in the mechanical engineering machine design course where charts and tables of experience factors deal with the many imponderable factors affecting a design. The students are advised to first consider the conveyability characteristics of a material, such as its angle of repose, angle of surcharge and flowability as well as its density, dustiness, wetness, abrasiveness, corrosiveness and temperature. It is shown how the belt width is determined as a result of load area for both troughed and flat belts. An expression for power requirement is presented and it is noted that the effective tension in the belt is the pertinent factor which the engineer must evaluate. How the effective tension is



affected by ambient temperature, idler friction, flexure of the belt and load over the idlers, length of the belt, weight of the belt and the load, height the material is to be lifted, acceleration of the material as it is placed on the belt and the load of accessories such as skirt board, plows and scrapers is detailed. Slack-side tension and idler spacing are also discussed.

Solid-Gas Separation

The students are advised about the various devices used for cleaning particulate solids out of a gas, including aero-mechanical separators, wet scrubbers, electrostatic precipitators and filters. Pressure drop, flow rate, grade efficiency and cut size were discussed and it was shown how they characterize devices used for solid-gas separation. The cyclone dry-separation device was described in detail. It was shown how on the basis of Euler and Stokes numbers, cyclones can be sized for a particular operation and how to determine if several cyclones have to be operated in parallel.

Gas Fluidization

The arrangement of a fluidized bed was detailed and the students were told about how these devices comprise a desirable means of conducting reactions in chemical processing. The use of aeratable, sand-like, cohesive and spoutable powders in fluidized beds was discussed. Bed pressure drop, minimum fluidization velocity, slugging, bed expansion, entrainment of solids in the exhaust and heat transfer were considered preliminary to giving the students a design example.

Suspensions and Sedimentation

Dr. Jonathan Luke presented an excellent lecture about sedimentation which is his research specialty. The concept of sedimentation was defined, Faxen's law was introduced, the angular velocity of a suspended particle considered and the "effective fluid" model of a suspension detailed along with the concepts of effective velocity and Einstein viscosity. Sedimentation was described by the super-dilute theory, the dilute theory and methods for enhancing sedimentation were noted.

Slurries and Suspensions

The forces acting on a particle in a fluid were considered to develop an expression for the terminal settling velocity of the particle. The concepts of drag coefficient and Archimedes number were introduced and correlations between them and settling velocity presented. Homogeneous suspensions, those in which the particles do not settle, were described. The various types of rheological behavior such as Newtonian, pseudoplastic, dilatant, and plastic, in homogeneous suspensions were illustrated. Also discussed were time-dependent rheologies such as thixotropy and anthixotropy. Viscoelastic behavior was also mentioned. The working equations for the various types of rheological measurement devices were developed, including the concentric cylinders, cone and plate and tube-flow geometries. The Newtonian, power-law, Bingham plastic and Casson constitutive equations were covered, along with the Arrhenius equation and temperature-reference method for dealing with the effects of temperature variation.

The mechanics of both the laminar and turbulent flow of suspensions in pipes was considered. The lecture on powder mixing in agitated tanks included a presentation of the relationship between the power required for mixing and the Reynolds number of the suspension. In the lectures about the hydraulic transport of suspensions, the phenomena of saltation and the pseudohomogeneous and heterogeneous regimes were described. Durrand's correlation between pressure drop and flow rate and his expressions for transition velocity and critical velocity were presented as design tools. The agitation of vessels to prevent settling was also



discussed and the Baldi and Conti expression for the critical speed of an agitation impeller reported to the students.

Particle Size Enlargement

After discussing the purposes of enlarging the size of particles and the increased use of such processes in industry, several methods of size enlargement were presented along with a consideration of how a choice among them is made. The mechanics of particle agglomeration as well as concept of nucleation were generally described. Tumbling was mentioned as an enlargement method. Inclined-disk agglomerators were described in detail, including the size-classification which occurs in their operation, their dimension, capacity and power requirements. Drum granulators and their operation were also covered.

Particle Size Reduction

The purposes of reducing the size of particles through crushing and grinding were stated along with the fact that the energy required in such operations is very high and sometimes become a critical factor. Other important aspects of choosing a size-reduction method is the size reduction grade, the degree of size reduction, hardness of the feedstock as specified by the Moh's scale, particle failure and product behavior characteristics. Various attempts to quantify the forces involved in size reduction such as interatomic forces, strain energy and crack length were covered in the lectures. The Rittinger, Kick, Bond and Holmes methods for estimating the amount of energy needed to drive a size-reduction process were considered and compared. The mathematics of predicting product size distribution was demonstrated for the students. Toughness, abrasiveness, feed size, cohesivity, adhesivity, particle form, softening and melting points, fat content, aromatic content, toxicity, flammability and explosiveness were detailed as factors to be considered in specifying a size reduction process. The various stressing mechanisms which reduce particle size were presented.

The lectures then proceeded to describe various crushing and grinding machines, including jaw crushers, gyratory crushers, cone crushers, roll crushers, rolling mills, table, bowl and pendulum roller mills, impact mills, hammer mills, disintegrator or cage mills, jet mills, pancake jet mills, loop or oval jet mills, target jet mills, jet mills with moving target, ball mills, rod mills, vibration ball mills, cutting mills, strand cutters, granulators, wet size reduction and agitated ball mills. A sample was given showing the students how to calculate the size distribution resulting in a hammer mill given the initial size distribution, breakage distribution functions and the run time.

Collision Mechanics

Dr. Rajesh N. Dave conducted a lecture on the collision of particles. The theory of colliding particles was discussed since this is an important constituent in dictating observed bulk behavior. The lecture began with consideration of stereomechanical impact, introducing the concept of coefficient of restitution. Equations were presented which describe the planar impact of spheres. It was noted that the stereomechanical approach did not yield the transient stresses, collisional forces, impact duration of collisional deformation which occurs.

Mindlin's study of the oblique contact of two frictional spheres was presented with discussion of the non-sliding contact and micro-slip and non-slip regions. This was followed by consideration of the normal collision of elastic spheres, collision of frictional elastic spheres and the collision of inelastic spheres (plastic deformation). Johnson's model for coefficient of restitution was reported to the students. Numerical examples for the various aspects of collision mechanics were presented. The importance of this subject for development of discrete element numerical simulations of granular materials was pointed out. Several video clips from simulation studies by Dr. Otis Walton [5] were shown to illustrate how different contact models can simulate



real behavior of granular flows. Several simple, practical demonstrations using materials with different frictional properties were made to demonstrate its importance in contact mechanics.

Student Projects

In the final class, the students presented reports on their projects. These included a wide variety of topics, representative of those covered in the course. Included were parameter studies for the Coulomb mechanics, comparative designs of bunkers and hoppers, detailed reports on Jenike's analysis, sample calculations for the selection of cyclones, surveys of viscometers, design of fluidized beds, design of conveyor belts, design of pneumatic conveying systems and computer simulation of bouncing ball.

Comments About the Undergraduate Course

The general reactions of the students to the course were favorable. While a firm foundation in theory was established for each of the major topics, there was a strong bias toward applications which the students recognized that they were likely to encounter when they enter industry. Indeed, several of the students were able to report to the class about their experience with particle problems which they had encountered in their part-time or summer employment. These reports indicated the relevance of the course material to industrial practice.

Conducting the course was not without its challenges. Covering a wide range of topics was difficult and required careful consideration of how much or how little detail would be presented for each individual subject. Since the course was to be application oriented, it had been hoped to give the class some demonstration experiments using the apparatus being acquired for the planned laboratory course, but most of that equipment was still being delivered during the term. Photographs, videos and case studies of actual industrial applications would also be highly desirable for this class and effort needs to be spent on obtaining them through the help of the members of the Advisory Board the next time this course is presented.

A single text book providing an overview of particle technology was not available and that lack placed considerable more burden upon the instructor and inconvenienced the students. Consequently the lectures were based on two books and a variety of other reference material. Nedderman's *Statics and Kinematics of Granular Materials* [1] provided excellent coverage of Coulomb materials, Rankine states and had a discussion of particle size and properties. However, that book did not cover the broad range of topics dealt with in the course. The anthology edited by Rhodes, *Principles of Powder Technology* [2] had chapters covering many aspects of handling particulates, including particle characterization, Jenike's design of hoppers, agglomeration, crushing and grinding, separation and fluidization. It was written for similar courses which had been introduced in England, and probably would have been adopted as the text for this course had the publisher been able to make delivery in time for the fall term. During the fall semester, Professor L-S Fan of Ohio State University kindly sent us a copy of his manuscript *Principles of Gas-Solid Flows*[3], as yet unpublished, which was very helpful.

Special Topics Course: Image Analysis for Applications in Particle Technology

This was an upper level graduate course that includes informal seminar style lectures and hands on laboratory sessions. The course material was derived from a number of text-books and research articles. The course was designed in a manner such that no prior knowledge in either Image Analysis or Particle Technology is required. The only prerequisites were undergraduate differential equations and competence in computer programming. The course was designed to have a good mix of theory and practice of image analysis techniques.



Although the emphasis was on applications in particle technology, students involved with experimental research in other areas could also benefit from this course.

The course covered some standard topics that include binary image analysis, binary image morphology, neighborhood operations, image segmentation, and edge detection. Other topics were boundary segmentation, motion analysis, pattern classification and clustering. Some of the specialized topics such as techniques based on fuzzy clustering, robust clustering and evidence collection (such as Hough transforms) were also considered. These techniques were considered specifically with an objective of detection of shapes such as circles and ellipses, since in many particle technology experiments, one must detect particles which are usually spherical. The course required that the students write a complete set of computer codes for binary image analysis for computing geometric as well as topological properties of binary images. They were also introduced to PC based commercial image analysis packages such as VISILOG (by Noesis Corporation) and OPTIMAS (by Optimas Corporation).

Comments about the Image-Analysis Course

Grading of the course was based on homework assignments, projects and an exam. The homework assignments and the exam were based mainly on the material covered in the class. The term project, however, was somewhat more specialized, and each student opted for a different topic. For this project, each student, in consultation with the instructor, selected from the current literature one or more archival papers that appeared to have a great potential for application to advanced image analysis for particle technology experiments. Each student then studied this material, and wherever feasible, either looked for related software through internet, or wrote his own codes to test out the author's claims. The project also required a professional 25 minute presentation from each student during the final week of the semester. In this presentation, the students were required to give an overall summary of the technical papers they studied, as well as their own appraisal of the material. Each presentation was followed by a question/answer session, and the students graded their peers for their presentation skills and the technical content. Their evaluation also counted towards the final grade in the project. The topics that the students selected included: computational design of optimal filters for edge detection as well as sub-pixel edge detection, use of Hough transforms for detection of motion of vibrated disks, particle motion analysis using optical flow as well as correlation technique, motion correspondence through Hopfield neural networks, free-form shape detection through active contours (SNAKES) as well as propagating fronts, and development of robust least squared error fitting techniques.

Eight students took this course for credit and one student audited the course. Four of these were Doctoral students, while the rest were Masters degree students. It appears that at least five students who took this class will directly help with the development of the Particle Technology Laboratory.

Special Topics Graduate Course in the Mathematics of Particle Technology

As mentioned earlier, as part of the NSF-CRCD effort to promote education in particle technology at NJIT and to build an infrastructure of knowledge in this area among graduate students of applied mathematics, Dr. Jonathan Luke of the Mathematics Department offered a graduate course entitled, "Special Topics in Applied Mathematics: Particle Technology" in the summer of 1995. This course contributed to the implementation of the project through development of course materials, experience with teaching the material to a multidisciplinary audience, and involvement of graduate students in particle technology. This course was targeted primarily at second-year Ph.D. students in applied mathematics, many of whom had just completed a course in mathematical fluid dynamics; nonetheless, formal prerequisites were limited to undergraduate



mathematics and fluid dynamics. This permitted a broader range of students to participate but restricted the depth of mathematics analysis that could be pursued.

Description of the Special Topics Course

The goal of the course was to develop a competence among the students in modeling fluid-particle flows and in determining the physical phenomena predicted by appropriate models. The course focused on sedimentation, shear flows, and flow in porous media with emphasis on the determination of macroscopic properties through analysis of microscopic models. Low Reynolds number models were emphasized, but students were forced to confront the limitations of Stokes flow through problems requiring alternative flow models; for example, students were asked to estimate the time required for water in an aquarium to settle adequately to perform a specified sedimentation experiment. The course began with review of modeling using the Navier-Stokes equations including formulation of boundary conditions and computation techniques in vector and tensor calculus. We then proceeded to consideration of the Stokes equations including the stokeslet and related singular solutions, Faxen's laws, variational and boundary integral formulations, explicit solutions of canonical problems such as a sedimenting sphere, a small particle near a wall, and a sphere in a shear flow. The remainder of the course used these results to analyze three fluid-particle systems. The mean sedimentation speed in a suspension of spheres was estimated for periodic and random suspensions using asymptotic and variational methods. The viscosity of a suspension was estimated using variational methods. Darcy's law for porous media flow was derived and its applications considered.

Comments About the Special Topics Course

The dozen graduate students beginning the course fell into three roughly equal-sized groups: advanced applied math students (two years or more of graduate study), intermediate applied math students (one year of graduate study), and engineering students with various levels of experience. Although only the advanced applied math students were able to fully achieve the goals of the course, the intermediate applied math students progressed substantially in appreciation for the use of the standard catalog of mathematical methods in the analysis for fluid-particle systems. The engineering students, none of whom completed the course, seemed unable to make a serious effort to learn the course material despite a substantial effort to accommodate their needs. Personal and institutional factors contributed to this situation, but the failure to bridge the disciplinary gap seemed to grow out of a lack of an intuitive sense on the part of the students that the material presented would contribute to their scientific or professional development.

We see several lessons in this experience. Presentation of this material to a multidisciplinary audience should be application based with techniques introduced when their purpose is clear. When possible students should come to courses of this kind with a substantial experience in implementing a project which depends in part on marshaling theoretical ideas to achieve a practical goal. We believe that the laboratory course under development, with its significant project component, should help student develop the scientific maturity needed to appreciate the theoretical materials found in our graduate course. Finally, our experience reemphasizes the need on the part of all in academia to make genuine sustained efforts to prepare students to take full advantage of the multidisciplinary workplace they are likely to encounter after graduation.

Integration and Synergy of Education and Research

One of the basic goals of the NSF-CRCD project is to integrate the particle technology research that has been conducted at NJIT and by other researchers over the last several years into the undergraduate and graduate courses described above. Therefore it is no coincidence that significant research activities in particle technology at NJIT have been ongoing for a number of years. There is an existing Particle Technology laboratory (PTL)



which is housed in the Mechanical Engineering Department. The Laboratory was established in 1990 with the receipt of a major grant from the US Department of Energy to develop a nonintrusive particle tracking system for use in granular chute flows. Since then it has greatly expanded its activities to include: (1) experimental studies involving a variety of dry granular phenomena as well as sintering of powders, fluidized beds, and control of particulate emissions, (2) granular dynamics modeling of dry bulk solids and (3) the development of diagnostic techniques, and image processing and pattern recognition algorithms. Many of these research project were described in our paper "Particle Technology Research at NJIT" published in the 1995 ASEE Annual Conference Proceedings [6]. However, in order to provide the impetus for even further expansion of our research and educational activities in the years ahead, NJIT has recently established a Particle Technology Center to provide the requisite support structure to achieve these goals.

Particle Technology Center

The mission of the particle Technology Center at NJIT is threefold:

- to conduct basic experimental research and mathematical modeling at the microlevel to gain an understanding of the macroscopic behavior of bulk solids in dry and slurry form,
- to educate undergraduate and graduate students and provide training to other professionals in the engineering practice of particle technology, and
- to develop cost effective flow, handling, and processing technology of particulate systems relevant to existing and emerging industries, and transfer this technology to industrial companies working in partnership with the Center.

The research activities of the PTL have been expanded by recruiting additional faculty from the Departments of Mathematics, Civil Engineering and Electrical Engineering to join the Center. Presently, the Center Staff consists of about ten interdisciplinary faculty, visiting scholars and post docs, graduate and undergraduate students, all working together on a variety of fundamental and applied research projects. These projects encompass broad areas such as: modeling and analysis of particle flow equations, granular dynamics simulation modeling, experimental studies on dry granular systems, analytical and experimental studies of vibrating granular flows, control of diesel soot and NO_x emissions, studies of fluid-particle suspensions, studies of fluid-fluid and fluid-solid mixing, particle-particle coating, sintering and agglomeration of particles at high temperatures, applications to plastics processing, applications in civil engineering such as the influence of fluids on the stress-strain behavior of granular materials like sand, as well as application in electrical engineering such as the use of VLSI in experimental instrumentation. Thus the long term goals of the Center include enhanced scholarly activities, including presentations, publications and intellectual property, submission of multidisciplinary federal and industrial proposals, broadening education and training, continuing laboratory development and modernization of experimental equipment, solicitation of corporate memberships, and expansion of center participation to enhance our expertise in particle technology.

In this context the Center has already established important ties with many industrial companies including Hoffman La Roche, SmithKline Beecham, Exxon, Alcoa, Dupont, Dow and others in order to forge partnerships with industry in terms of collaborative research, input into our educational programs and technology transfer. Additional faculty from outside of NJIT, with special expertise in different areas of Particle Technology, from Rutgers University, the University of Pittsburgh, the University of Arizona and the University of Florida's NSF Engineering Research Center have also expressed interest in working with the Center. Furthermore, recent collaborations, such as a joint proposal to work on a coal soot monitoring project with



Northeastern University, and experimental granular flow research using NMR (Nuclear Magnetic Resonance) imaging at Lovelace Institute of Albuquerque, New Mexico, hold much promise for expanding the scope of the Center. Lastly, because of the highly diverse student population at NJIT, the Center will serve to channel a large number of talented under-represented minority and women students into the particle technology field. Current information about the center can be obtained through the web page at address <http://www-ec.njit.edu/~adr7805/PTL.html>.

The synergism between the NSF-CRCD program and the establishment of the Particle Technology Center is clear; we must maintain a leadership position in Particle Technology in order to successfully carry out the objectives of the CRCD program. The Particle Technology Center provides the infrastructure to accomplish this.

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