PARTICLE SCIENCE AND TECHNOLOGY EDUCATIONAL INITIATIVES
At the University of Florida

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The NFS Engineering Research Center (ERC) for Particle Science and Technology at the University of Florida addresses the need for students trained in particle science through interdisciplinary, multi-faceted educational initiatives. Particle Science and Technology is a term that has something for everyone. The term is so broad and the engineering disciplines in which it is relevant are so many that no single discipline can supply the resources and expertise (or room in the curriculum) to cover the field adequately. In chemical engineering alone, "particle science and technology" makes its appearance directly or indirectly in numerous contexts, such as fluidization operations, particulate separation phenomena, and colloidal and interfacial phenomena, to name a few.

The importance of particle science and technology to the practicing engineer has been articulated effectively.[1,2] As Ennis, *et al.*,[1] point out, a graduating engineer seldom sees examples of the unique problems particle-based processes pose in industry (*e.g.*, stability of dispersions, transport of powders, granular materials or slurries, mixing of particles, and separation of liquids or solids in finely divided form dispersed in a fluid, to name a few).

As is well known now, the prevalence of particle-based processes and operations in science and industry has also brought to the forefront the role of surface and interfacial phenomena and fluid/particle (*e.g.*, microhydrodynamics) and particle/particle interactions. Their importance has been recognized for a long time in colloid science, but their role in others areas (*e.g.*, tribology, friction, synthesis of advanced materials, and cleaning microelectronic substrates) is no less significant. What is also important is to introduce the students to the fascinating array of modern instrumentation and analytical techniques that has emerged in recent years. For example, the development of scanning tunneling microscopy and its many offshoots has opened up possibilities hereto unimagined (*e.g.*, measurement of atomic forces and manipulation and imaging of atoms, molecules, and particles on surfaces). This also implies that at least some basic principles of the methods be introduced in courses so that the students can appreciate these new tools and their unexplored possibilities.

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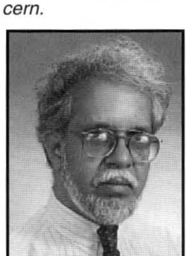

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INSTRUCTIONAL MODULE SERIES

How does one make room in an already overcrowded curriculum for these materials? Where does one go for resources in specialized areas to supplement what is currently available? How does one encourage a faculty member to prepare instructional materials when universities rarely encourage, in a real and substantial manner, the preparation of textbooks or other educational aids? Is there a way to develop instructional materials that can also be used in continuing education courses in industry? Such questions have formed the motivation for development of an "Instructional Module Series Program" at the ERC.[3]

The instructional modules are reasonably self-contained educational aids suitable for two or three one-hour lectures on a sufficiently narrowly focused topic in particle science and technology. Each module typically includes, in addition to text and figures, worked-out examples, quizzes, end-of-the-module review questions, and annotated references. The level of the modules may vary and can be restricted to undergraduate or graduate materials or materials suitable for continuing-education courses. The last includes modules written for industrial researchers as well as those targeted to plant-level personnel.

Currently, the modules are prepared in printed form as attractive booklets, but other media may be considered in the future. We have published two modules so far,[4,5] and plans for others are underway. The table of contents of the first module is presented in Table 1. The ERC is currently recruiting potential authors from both academia and industry and will provide compensation for manuscripts accepted for publication as a module by the ERC as part of the instructional module series.

INTEGRATION OF INSTRUCTIONAL MODULES IN COURSES

The module program is meant to address a number of difficulties an instructor faces in preparing instructional material and in developing courses. Since the modules are short in length and narrowly focused in terms of topics, they require significantly less time for preparation, and faculty members and industrial scientists and engineers can afford the time needed to prepare them.

The modular form of the material also makes it easy for using the material in standard courses; if the curriculum does not permit room for new courses, at least some of the essential elements of the area can be introduced in other courses. Some examples of such possibilities are:

- *The viscosity of dispersions is seldom discussed in many engineering courses, but a module on the Einstein equation for viscosity of a dilute suspension and on the Krieger-Dougherty equation for concentrated dispersions[6] can easily be incorporated in any standard course in fluid mechanics.*
- *Similarly, a module on aggregation kinetics can serve as an example of how standard kinetic equations (typically taught in a course on chemical engineering kinetics) help in developing 'population balances' and evolution of size distribution in colloidal or aerosol dispersions.*
- *Undergraduate thermodynamics courses introduce the concept of second virial coefficient and illustrate its use in solution thermodynamics. But if a module on osmotic pressure, turbidity measurements, and Zimm plots[6] is available, the thermodynamic courses can be used as vehicles to introduce a particle science example and to illustrate the use of thermodynamic concepts in the characterization of particulate systems.*
- *The comminution module outlined in Table 1 finds a natural place in a course on unit operations in chemical engineering as a particle science example as well as an illustration of the use of rate equations and mass-balance equations.*

Of course, these are only a few of the many possibilities.

TABLE 1
Contents: Instructional Module on Comminution[5]

Introduction to the Principles of Size Reduction of Particles by Mechanical Means

1. The importance of size reduction in particle processing
2. The relationship of size reduction to basic physics
3. General approaches to grinding-equipment selection, design, analysis
4. Representing particle-size distribution data
5. Mechanistic size-reduction concepts
6. Introduction to breakage rates
   - The first-order breakage hypothesis
   - Impact of media size and composition on breakage rate
   - Other factors influencing breakage rates, including rheology
   - Mill capacity as a function of breakage rate
7. Progeny fragment distributions
8. Introduction to rate mass-balance modeling
9. Advantages of batch and continuous operating modes
10. Practical comminution guidelines
11. Types of size-reduction machines
    - Tumbling media mills
    - Hammer and rotary cutting/shredder mills
    - Stirred-media mills, including attrition mills
    - Vibratory mills
    - Fluid energy and jet mills
12. Summary

Review Questions
References

PARTICLE SCIENCE AND TECHNOLOGY COURSES

Because of the existing activities in the area of colloids and surfaces, the curriculum at the University of Florida has included for a number of years a two-credit course on interfacial phenomena, "Particulate Interfacial Systems: Science and Engineering." This course, primarily at the undergraduate level but also taken by graduate students unfamiliar with the subject, consists of a general introduction to colloids, micelles and microemulsions, colloidal and surface forces and surface tension, and related interfacial phenomena.

A more elaborate course is also under development based on a book by Hiemenz and Rajagopalan.[6] The first chapter is designed to be sufficiently general to offer a broad introduction to particles and colloids. It also includes 21 'vignettes' (about a page each) that highlight the interdisciplinary impact of particle science, colloids, and surface science and, further, illustrate their use in a broad array of applications ranging from environmental remediation and xerography to targeted drug delivery and molecular recognition. An example is shown in Table 2.

In addition, a new graduate-level course on colloid physics has been introduced into the curriculum. In contrast to conventional courses on colloids, this new course focuses on an introduction to liquid-state physics and its applications in understanding structure, phase transitions, and properties of concentrated or strongly interacting colloidal dispersions.

Courses on colloids and interfaces are relatively well established in the chemical engineering curriculum in many universities,[8] but the same cannot be said of the somewhat more broadly defined area of 'particle science and technology.' In order to present a general overview of at least some of the topics in particle science and technology, we have introduced a new course, "Particle Science and Technology: Theory and Practice"; it carries course numbers identifying eleven engineering and science disciplines (aerospace engineering, agricultural engineering, coastal and oceanographic engineering, chemical engineering, chemistry, computer and information science, environmental engineering, materials science and engineering, mechanical engineering, microbiology, and physics), reflecting the interdisciplinary nature of both the subject and the ERC. These multiple listings allow both upper-level undergraduate and graduate students from a wide variety of departments to enroll for the class through their respective departments, thereby improving the accessibility of the class to interested students.

The course is strengthened by the fact that it is team-taught by engineering faculty and an industrial representative. The inclusion of an industrial representative in the teaching team results in a strong applications component in the course. It is taught on a level that allows students from various disciplines to learn basic concepts in particle science and technology. Student discussions of their respective research projects during the semester further enrich the interdisciplinary focus of this experience.

Course materials currently in use include course notes provided by the instructors and the instructional modules described above. A topics listing for the course is shown in Table 3. A laboratory manual, developed to supplement the lectures, includes experiments on grinding in media mills, magnetic separation, powder density, effect of chemicals on filtration, principles of solid/solid separation by flotation, zeta potential measurements, and viscosity measurements.[9]

An additional course, "Optimization , Scale-Up, and Statistical Experimental Design," has also been developed. It teaches these topics through extensive use of particle science applications. Grinding, extractive metallurgy, powder mechanics, composite materials issues, environmental engineer-

TABLE 2
Vignette on Sedimentation Field Flow Fractionation (adapted from [6])

Were it not for the never-ending, gentle tussle between gravity and diffusion, our planet would not have an atmosphere, nor would we be here to reflect upon it! The *barometric equation,* which describes this 'balance of power' between the above two well-known phenomena, is derived in most introductory physical chemistry books and is mentioned in the closing paragraph of Chapter 2.[6] There are many more life-sustaining processes that are affected by or rely on sedimentation and diffusion, but frequently it is the more mundane 'practical' consequences of these phenomena that attract our attention. One such consequence is their use in physical characterization of colloidal dispersions and macromolecular solutions. Let us highlight one such application through one member of a class of analytical separation techniques known as *Field Flow Fractionation.*

The name Field Flow Fractionation (abbreviated to FFF) stands for a family of techniques, invented in the 1960s, that take advantage of the response of colloids and macromolecules to electrical, thermal, flow, or centrifugal fields to produce a chromatography-type separation of the particles.[7] In a typical setup, a suitable force field is applied in a direction normal to the axis of a thin chamber that contains the dispersion. The field forces the particles against one of the walls of the chamber, and, at steady state, a concentration profile is set up in the direction of the applied field as a consequence of the differences in the responses of the various species in the dispersion to the applied field. The particles are then eluted by flowing an elutant fluid through the chamber. The fluid velocity decreases progressively from the axis toward the accumulation wall because of friction at the wall. And, as a consequence, the particles are carried along the axis at different velocities depending upon their distance from the accumulation wall. For example, the component closest to the accumulation wall lags behind the one near the center of the chamber (see Figure 1). Samples can now be eluted through a detector or collection device. The detection is usually based on changes in standard properties such as refractive index or light absorption.

One of the more advanced of the FFF techniques is the *Sedimentation* FFF (SdFFF) in which the applied field is a centrifugal force (see Figure 1). A typical separation achieved through SdFFF is also illustrated in Figure 1. SdFFF is suitable for species with molecular weights larger than about 10^6 and has proven to be useful for a large number of biocolloids (*e.g.,* subcellular particles), polymers, emulsions, and natural and industrial colloids. As we shall see soon, gravitational and centrifugal sedimentation are frequently used for particle-size analysis as well as for obtaining measures of solvation and shapes of particles. Diffusion plays a much more prevalent role in numerous aspects of colloid science and is also used in particle-size analysis, as discussed in the context of dynamic light scattering in Chapter 5.[6] The equilibrium between centrifugation and diffusion is particularly important in analytical and preparative ultracentrifuges.

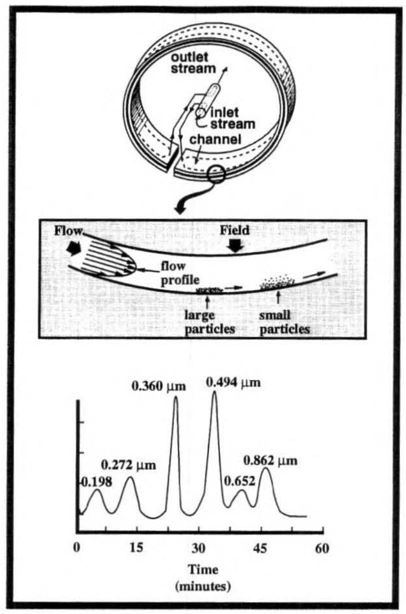

Figure 1. *Sedimentation Field Flow Fractionation (SdFFF): a schematic representation of an SdFFF apparatus and of the separation of particles in the flow channel. A typical fractionation obtained through SdFFF using a polydispersed suspension of polystyrene latex spheres is also shown (adapted from Ref. 7).*

ing problems, and statistical process control are some of the many particle science and technology problems that the students explore while participating in this course.

PARTICLE SCIENCE AND TECHNOLOGY INTRODUCTORY TEXTBOOK

The ERC recognizes the need for an introductory-level textbook to be used in a class such as described above. Therefore, a textbook is under development (*Introduction to Particle Science and Technology,* by Richard Klimpel). It is being written from the perspective that particle science and technology is a critical part of the education and training of students from a variety of engineering and scientific disciplines. Given this interdisciplinary focus, the book is being designed to be accessible to students across the wide range of disciplines and at the same time provides references that direct students to further, more specialized resources. The book will allow students with standard university-level science and mathematics backgrounds to become familiar with particle science and technology concepts in a challenging, but not technically overwhelming, introduction.

TABLE 3
Topics: Introductory Particle Science and Technology Course

Section 1	"Introduction to Particle Systems" *(the nature of particle technology and why particles are important in our lives)*
Section 2	"Representing Characteristics of Individual Particles and Particle Assemblies" *(particle size and shape, descriptions of particle-size distributions)*
Section 3	"Methods of Particle Characterization" *(optical, diffraction, physical techniques)*
Section 4	"The Chemical Nature of Particle Surfaces" *(surface charge, electrokinetic phenomena, surface potential determination, colloidal forces)*
Section 5	"Chemicals Used in Particle Systems" *(coagulants, flocculants, dispersants, surfactants)*
Section 6	"Surface Modification of Particle Systems" *(wettability, adhesion strength, uniformity of coatings, emulsions)*
Section 7	"Methods of Particle Representation" *(nucleation, crystallization, gas- and liquid-phase synthesis)*
Section 8	"Reducing Particle Size by Comminution" *(the nature of breakage, description of breakage processes, and various approaches to size reduction)*
Section 9	"Separation of Particulate Systems" *(solid/solid and solid/liquid separation by chemical means, methods of classification, gravity-based separations)*
Section 10	"Packing of Particles" *(physical forms, compaction, interactive forces)*
Section 11	"Transport of Particle Systems: *(heat, mass, and momentum transfer; rheology and flow of dry powders of suspensions)*
Section 12	"Environmental Aspects of Particle systems" *(filtration, aerosols, solid/gas separation)*
Section 13	"Technology Applications of Particle Systems" *(case studies from different industries)*

RESEARCH-ORIENTED EDUCATIONAL PROGRAMS

A key component of the ERC education effort is providing students with the opportunity to participate in hands-on research in particle science and technology. Since 1994, over 200 undergraduate students from 14 different departments have participated in particle science and technology research labs. These students are developing the skills necessary to work in interdisciplinary research teams and to improve their written and oral communication skills through research presentations and reports. This program supports students for multiple semesters, resulting in a solid particle research component in the education of these undergraduates.

The development of teaching materials such as the instructional module series and textbook, the addition of particle science and technology courses to the university curriculum, and enhancement of the undergraduate education experience through hands-on, team-research projects are part of the ERC commitment to improving student preparation for work in the field of particle science and technology.

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REFERENCES

(Information on References 3-5 and 9 can be obtained by writing to Publications Coordinator, ERC for Particle Science and Technology, 418 Weil Hall, University of Florida, Gainesville, FL 32611-6135 (e-mail: erc@eng.ufl.edu)

1. Ennis, B., J. Green, and R. Davies, "The Legacy of Neglect in the U.S.," *Chem. Eng. Prog.,* **90**(4), 32 (1994)
2. Nelson, Jr., R.D., R. Davies, and K. Jacob, "Teach 'Em Particle Technology," *Chem. Eng. Ed.,* **29**, 12 (1995)
3. Rajagopalan, R., Series Editor, *Instructional Modules in Particle Science & Technology,* ERC for Particle Science & Technology, University of Florida, Gainesville, FL (1997)
4. Klimpel, R., Instructional Module, *Chemicals Used in Particle Systems,* ERC for Particle Science & Technology, University of Florida, Gainesville, FL (1997)
5. Klimpel, R., Instructional Module, *Introduction to the Principles of Size Reduction of Particles by Mechanical Means,* ERC for Particle Science & Technology, University of Florida, Gainesville, FL (1997)
6. Hiemenz, P.C., and R. Rajagopalan, *Principles of Colloid and Surface Chemistry,* 3rd ed., Marcel Dekker, New York, NY (1997)
7. Giddings, J.C., *Unified Separation Science,* Wiley, New York, NY (1991)
8. Woods, D.R., and D.T. Wasan, "Teaching Colloid and Surface Phenomena—1995," *Chem. Eng. Ed.,* **30**, 190 (1996)
9. El-Shall, H., ed., *Particulate Characterization Laboratory Manual,* Engineering Research Center, Gainesville, FL (1997) ❐