TEACH 'EM PARTICLE TECHNOLOGY

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Particles are critical to the success of many products, but the U.S. chemical industry lags behind its foreign competitors in the understanding and application of particle science to chemical process technology. This is due, in part, to the neglect of particle science and technology in the education of scientists and engineers. Although most chemical processes involve particles, the typical U.S. chemical engineering curriculum devotes little time to particle technology. Consequently, new particle processes have dismal prospects for startup compared to liquid and gas processes, and our engineers must struggle to optimize and retrofit existing production facilities that process particles.

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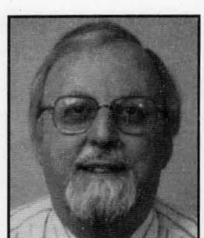

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***Karl Jacob** is Research Leader with the Dow Chemical Company. He has devoted eleven years to understanding particle processing. In 1988 he founded the Solids Processing Lab, which provides support to Dow's engineering, research, and manufacturing communities. He specializes in solving problems related to drying, fluidization, bins, hoppers, and powder flow.*

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We propose that the present set of undergraduate courses in chemical engineering be modified to include more problems illustrating the challenges posed by particle processes and exploring practical routes to their resolution. Eventually the curriculum should also include a separate course providing an integrated approach to engineering applications of particle technology.

WHAT IS PARTICLE TECHNOLOGY/SOLIDS PROCESSING?

Table 1 outlines the technical areas of particle technology. We have found that some areas of powder technology are virtually absent from U.S. engineering curricula: powder storage, Jenike's theory of hopper flow, cyclones, dilute phase conveying, fluidization, and powder milling.

Particle technology is becoming increasingly important. As the microcomponents of information retrieval, expert systems, medical diagnostics, and robotic manufacturing and surgery become more sophisticated, the need for carefully controlled structures has created an enormous market for particles smaller than a micrometer in diameter. Modern agricultural, ceramic, pharmaceutical, and medical diagnostic materials require sophisticated control of particle size and agglomeration so that they can release ingredients on a well-defined schedule. Conversion of what was once considered waste into products useful to society often relies on sophisticated particle-generation and control schemes.

Customer needs and specifications for more mundane commercial products (pigments, plastics, pharmaceuticals, detergents) have become more stringent as companies seek to increase the effectiveness and to reduce the environmental impact of their products. Companies that cannot adequately control particle characteristics will lose market share to those companies who technologists have a better grasp of particle technology.

There will be many opportunities to apply particle technology to

- *Introduce differentiated products at a premium price based on carefully tailored particle properties or size distributions*
- *Reduce scale-up time and cost by understanding what basic data must be acquired and what full-scale processes best implement the unit operations developed at lab-scale*
- *Reduce rework costs by having meaningful specifications and process controls to make particles "right" early in the process*
- *Improve quality control and reduce environmental problems by improved sampling and on-line monitoring for properties critical to efficient operation*
- *Increase capacity and reduce costs by tailoring product properties to give higher solid-liquid separation rates, shorter drying times, and lower yield losses.*

Textbooks designed for undergraduate courses on particle technology include *Principles of Powder Technology*[1] (used by the Institute of Chemical Engineering in Great Britain for their post-graduate training course) and *Bulk Solids Handling*.[2] Unfortunately, neither book contains any problems.

WHY DO DUPONT AND DOW CARE ABOUT PARTICLE TECHNOLOGY?

DuPont and Dow are the fifth and sixth largest chemical manufacturers in the world (after BASF, Bayer, Hoechst, and ICI). Together, Dow and DuPont spent about $2.4 billion on research and development in 1991—half the entire total for the US chemical industry and ten times the amount of federal support for university non-defense research and development in chemistry and chemical engineering.[3] A 1985 survey found that about 60% (by value or volume) of the products sold by DuPont are sold in particulate form, while another 18% have particulate additives. Some 50% (by volume) of Dow's products are solids. The amount of solids handled is three to four times the amount finally sold when raw materials, intermediates, and minimal-value coproducts are considered.

DuPont and Dow operate several thousand major unit operations involving particulates, each one requiring supervision by a technologist who understands the relevant areas of particle technology. In 1988 DuPont designated particle technology as one of its core technologies (critically important to success in global competition), and Dow constructed a solids processing "technology well" (to focus technical resources).

Because it is difficult to find US graduates adequately trained in particle technology, we must spend considerable time training people in particle technology and we recruit a disproportionate number of such specialists abroad (compared to national vs. international sales dollars). Some 40% of the engineers in the DuPont Center for Particle Science and Technology were trained abroad, and Dow's Solids Processing Center is located in Europe. Those US companies which are not multi-national must rely on post-college training and the rather small flow of US graduates who are trained in particle technology. All of us would benefit if US

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TABLE 1
Technical Areas of Particle (Powder/Slurry/Emulsion) Technology

Characterization ◆ Sampling methods and statistics; methods for determining and characterizing particle size distribution, shape, surface roughness, porosity; packing in heaps and sediments; particle charge; adsorbed material; interfacial tension; granule strength/attrition/deformation

Powder Storage ◆ Angle of repose; hopper discharge; fines percolation

Mechanical Transport ◆ belt/bucket/screw conveyors; flowability; dynamic weighing; power consumption; selection based on particle size/shape/strength of agglomeration

Convective Transport ◆ sedimentation rate and solidosity; suspension in stirred tanks; rheology of slow-settling slurries; cyclone separation; dilute and dense-phase flow in pipes; static generation and dust explosions; flow-enhancement additives; fluidized beds, fluid flow through packed beds; erosion; selection/designing of valves/pipes/pumps; metering

Flocculation/Agglomeration ◆ Interparticle and interface forces; polymer adsorption and bridging; wetting and capillarity; floc strength and structure; granulation, briquetting, and tabletting

Deflocculation/Deagglomeration/Grinding ◆ Dispersion stability; grinding aids; particle fracture strength and toughness

Foam/Emulsions/Fouling ◆ Interfacial tension (interface energy); effects of surface curvature on solubility and vapor pressure; adsorption isotherms; foam/antifoam additives; froth flotation; emulsion formation and coalescence; decanter designs

Drying ◆ Capillary flow and compression; solubility and salt transfer; moisture diffusion and vaporize-condense cycling effects; use of convection to speed drying; heat transfer; induction heating; freeze drying; displacement drying

Mixing and Blending ◆ Effects of component size, shape, and density on blend time; gas release during wet-in; considerations in mixer design; demixing during flow; achieving remixing or resuspension; power consumption; rate of dissolution

Coating ◆ Alternatives to dry blending; caking, dusting, binders, slurry flow and drying in film coaters; film surface defects caused by particles

Solid-Fluid Separation ◆ Selecting solid-liquid separation equipment; sedimentation; cyclones; electroseparation; cake formation and structure; washing and dewatering the cake chemical engineering curricula were stronger in particle technology.

ARE SOLIDS HARDER TO PROCESS THAN GASES OR LIQUIDS?

Very definitely yes! The presence of particles introduces considerable complexity (compared to particle-free gases and liquids) into the selection of equipment and also into the estimate of the complexity and cost of operation and maintenance. Areas of particular concern are powder flow from bins, pneumatic conveying, metering, valves and pumps for solids and slurries, mixing and wetting-in, pipe plugging under low flow or shut-down conditions, and quality control. Particles can cause problems with commercial-scale operation that are not evident during laboratory or even pilot-scale tests, so someone skilled in particle technology should be involved with development of a new process from the earliest stages of research.

In a study of forty industrial startups, E.W. Merrow found that processes involving particles took several times longer to start up than those involving liquids or gases,[4] even though manufacturers anticipated problems and planned lengthier startup times for those projects! Plants involving several new unit operations were particularly hard to start up, and some particle processing plants have been abandoned (without producing any significant amounts of product) after tens of millions of dollars had been spent trying to make them work.

Merrow suggested that much of the problem is due to a lack of fundamental understanding of particulate phenomena and to a lack of applied research in this area. Inventors assume that engineers will take care of any awkward details of powder technology during scaleup, and the engineers assume that designers will solve the problems. In the end, the production staff is left to cope with a marginally operable system.

DO U.S. UNIVERSITIES TEACH PARTICLE TECHNOLOGY?

Unfortunately, no. In our recruiting visits to many campuses over the past four years we have found no U.S. university with a full undergraduate program in particle technology. Michigan Technological University offers an elective course every other year, and a few other universities offer graduate-level courses in agglomeration and fluidization. A recent study found that the average engineering curriculum provides less than twenty minutes of discussion on solid-liquid separations.[5] The distribution was found to be quite uneven—most schools had no discussion, while a few had several hours.

The strongest programs in particle technology are found in the departments of Mining and Mineral Science. But the courses on size reduction, agglomeration, and particle-liquid separation tend to ignore the molecular aspects of particle technology since few mining engineers pursue careers in the chemical industry. Chemical engineering courses on crystallization, solid-liquid separation, drying, and bulk handling focus on mass and energy balances and tend to ignore the mechanical aspects of particle technology, population balance, pore-size distribution, agglomerate strength, and the structure of packed beds.

Other nations recognized the importance of particle technology several decades ago and now have well-established programs. Japan has courses in powder technology in 24 of

TABLE 2
Introductory Course in Powder Technology

Outline of a typical one-year undergraduate course in powder technology at a German technical university, comprising 90 hours of lecture, 30 hours of discussion, and 12 half-day experiments.

PART I
When Fluid Is Not a Major Factor

- ¤ Description of Particulates
  - Single particle size/shape
  - Measuring/modeling size distribution
- ¤ Separation of Solid/Solid Mixtures
  - Mass balance
  - Separation parameter
- ¤ Mixing of Solids
  - Mixture types/statistics/sampling
- ¤ Size Reduction/Grinding
  - Surface energy/cracks/fracture strength distribution
  - Energy efficiency, equipment
- ¤ Size Enlargement/Agglomeration
  - Types of particle bonding
  - Equipment/applications
- ¤ Storage and Bulk Flow
  - Stress/shear/friction/bridging
  - Angle of repose, mass/funnel flow
  - Design of hoppers/silos

PART II
When Fluid Must Be Considered

- ¤ Two-Phase (Solid/Fluid) Flow
  - Drag/flow/settling
  - Pressure drop in fixed/fluidized beds
- ¤ Size Classification/Composition Sorting
  - Sifting (cross/counter-current)
  - Differential sedimentation/centrifugation
  - Magnetics/flotation
- ¤ Separation of Solids from Fluid
  - Settling/filtration
  - Spray scrubbers/electrostatic precipitation
- ¤ Fluidized Beds
  - Principles/nozzle patterns
  - Gas vs. liquid
  - Applications to catalysis/combustion
- ¤ Pneumatic Conveying
  - Dense/dilute phase
  - Continuous/slug
  - Pressure/vacuum systems
- ¤ Solid/Fluid Mixing
  - Impeller design/power use
  - Wetting, dispersion
  - Heat/mass transfer

its 38 universities, and 16 government institutes have strategic programs designed to aggressively focus on and capture markets that are dependent on particle technology.[6] There are strong programs in Europe at Delft and Twente (The Netherlands), Bradford, Surrey, and Loughborough (Great Britain), Hamburg-Harburg, Clausthal, Karlsruhe, and Braunschweig (Germany, where thirteen universities have powder technology programs), and in Canada at McGill, Laval, British Columbia, and Western Ontario. A typical curriculum is given in Table 2.

WHAT TOPICS ARE VITAL FOR YOUNG ENGINEERS?

Society's mastery of each area of technology goes through several stages. At first, mastery increases slowly as researchers explore the basic phenomena (the *emerging* stage). Then mastery increases rapidly as major quantitative theories are utilized (the *vital* stage), and finally, mastery levels out as the area is so well studied that new understandings are rare (the *mature* stage).

The ***emerging*** stage covers science where the markets are still uncertain, where there is a question of what variables are important in controlling the process, and where the processes for commercial production have not been designed. There is no organized body of understanding for the area, so there is little justification for including it in an undergraduate engineering curriculum. New developments cover wide areas and are patented to protect them from use by competitors, and production volumes are low. Current examples include genetic engineering, superconductor applications, and supercritical extraction.

The ***vital*** stage covers processes that are widely used but which often cause operating problems. Basic theories and models exist, but applying them to commercial processes is a challenge. Capability is developed incrementally, and competitive advantage is maintained by treating new developments as trade secrets. Current examples include slurry flow, agglomeration, crystallization, filtration, and milling (especially the kinetics of breakage). We are beginning to build quantitative models to predict the behavior of commercial-scale particulate processes. Expert systems and parallel processors can help chemical plant operators anticipate problems and decide on the best response, and some particulate processes are now run under computer control.

The ***mature*** stage covers areas that have been reported extensively in the technical literature and are widely and confidently practiced to design commercial equipment that operates trouble-free and well within the limits of past experience. Expertise and equipment are available from many sources at a lower cost than developing and maintaining the capability in-house (unless the company plans to specialize in the area). Current examples include pumps for gases and liquids, distillation towers, heat exchangers, ion exchange columns, gas adsorption beds, refrigeration units, and electric motors.

For emerging technologies, teaching can be restricted to the basic concepts. As areas move from the emerging to the vital stage, they should receive increased attention in engineering curricula since it is the application of vital technologies that provides industry with the greatest competitive advantage. As areas move into the mature stage, their place in the curriculum should be pruned back. The natural temptation to "overteach" mature technologies must be resisted; all that is needed is to make the fundamental principles clear and to describe the range of applications for commercially available technology. The elaborate design protocols for mature technologies are best taught within the companies that specialize in applying them.

TABLE 3
Examples of Industrial Support for Nonproprietary Studies in Particle Technology
(Authors will provide addresses on request.)

- → International Fine Particle Research Institute
- → Association of Crystallization Technology
- → American Filtration Society
- → Separation Process Services
- → Particle Technology Forum of the American Institute of Chemical Engineers
- → Colloid and Interface Science Division of the American Chemical Society
- → Gordon Research Conferences on Colloid Science
- → Center for Microengineered Ceramics (University of New Mexico)
- → Consortium for Advanced Materials Processing (Clarkson University)
- → Particulate Materials Center (University of Pennsylvania)

HOW CAN INDUSTRY HELP ACADEMIA?

The U.S. has become increasingly aware of the importance of particle technology. In 1973 a group of international filtration experts strongly urged more research and education in solid-fluid separation.[7] In 1988 the U.S. National Research Council Committee on Separation Science and Technology recommended focused research in six specific areas of solid-liquid separations.[5] Industry now provides a great deal of financing for nonproprietary research in particle technology (see Table 3), and many industrial practitioners (including the authors) regularly teach continuing education courses in particle technology. It is now time for U.S. universities to respond to the need by increasing the emphasis on particle technology in their curricula.

Although industry would like to achieve overnight what our competitors have built up over decades, we realize that gradual change is more likely. For example, classes in fluid mechanics could introduce consideration of dilute-phase gas and slurry transport. For the longer term, the National Science Foundation is supporting a joint academic-industrial effort to develop undergraduate courses in particle technology. Four week-long workshops will be held in 1994 and 1995, each helping twenty-five engineering faculty build elements of particle technology into their courses. The teams are DuPont and Penn State University, 3M and the University of Minnesota, Dow and the University of Houston, and Westinghouse and the University of Pittsburgh.

HOW MIGHT YOU RESPOND?

First, in the academic tradition, take this quiz:

- *Have you included examples of the relationships between particle size distribution, state of agglomeration, and end-use properties in your lectures, in required reading, in labs, and in homework?*
- *Have your graduates learned enough about particulate operations to participate on a startup team without extensive additional training?*
- *Can your graduates design a dust collector, a slurry transport line, or a storage vessel for a cohesive powder?*
- *Can your graduates make a computer model for the behavior and control of a process involving particles?*
- *Are your graduates aware of the typical problems encountered in systems involving particles and do they know enough of the terminology to discuss the problem with a consultant in powder technology?*
- *Have your graduates learned the most meaningful parameters to monitor and what options exist for resolving typical problems?*

Options for enriching the curriculum include

- *Permitting students to take (and count as electives toward a degree) courses in other departments, such as mining engineering, which already have strong courses in particle technology.*
- *Assigning the chemical engineering department to focus exclusively on gas and liquid processes and starting a new department devoted exclusively to particle technology, as is done in Germany.*
- *Developing continuing education courses in particle technology to be taught on campus, at a local corporation site, at AIChE meetings, via satellite through the National Technological Institute, or at a "for-profit" training center such as the Center for Professional Advancement.*

We hope that this paper will inspire you to act. If you can educate engineers to function effectively in this area of critical need, the U.S. chemical industry will hold onto its substantial share of the world chemical market, enhance the employment opportunities for technologists and plant workers, and increase the support for academic research in particle technology.

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ChE book review

ANALYSIS AND DESIGN OF DISCRETE LINEAR CONTROL SYSTEMS

by Vladimir Kucera

Prentice Hall, 472 pages, $66 (1992)

Reviewed by

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The subject of this book is the analysis and design of control systems for systems characterized by linear, constant coefficient, discrete-time models. It is assumed that the systems are perfectly modeled and unconstrained; the "modern control theory" approach [*ca.* 1960s with some recent (early 1980s) results] is used.

The intended audience for the book, as stated by the author, includes "the graduate student who intends to specialize in linear control and the practicing engineer or applied scientist who is interested in new perspectives of linear control theory. For the specialist, the book is intended as a reference and, hopefully, as an inspiration for further research." It is assumed that the reader has a background in abstract and linear algebra, linear system theory, and stochastic processes.

I liked the author's philosophy of placing bibliographical notes at the end of each chapter rather than disrupting the presentation of material with references. The text portion of each chapter is concisely written, with the bulk of the material dominated by mathematical equations. Beginning students may have trouble using this text for self-study since they will typically need more motivation and justification for the derivations.

Another aspect of the book that I liked were the problems at the end of each chapter. Short answers and more detailed solutions to all of these problems are provided in appendices. I found it odd that the author bothered to include the short answers section (eight

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