



DON PAUL

of the University of Texas, Austin



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DON PAUL

... of *The University of Texas at Austin*

WILLIAM J. KOROS

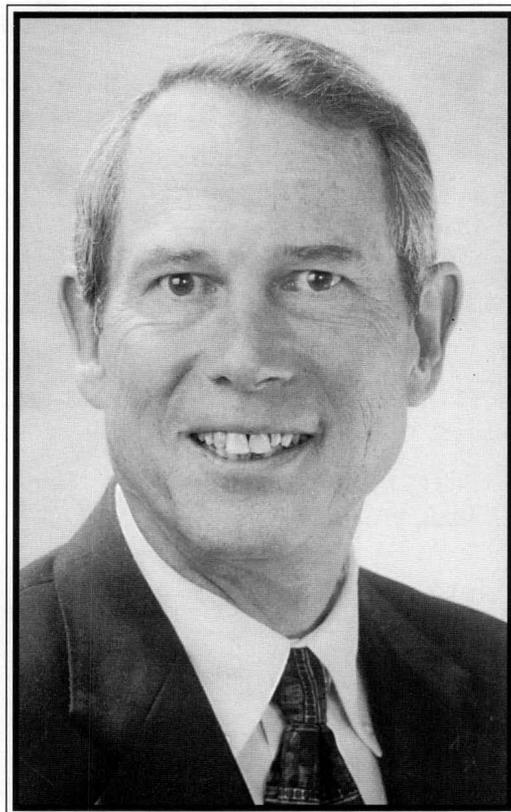
The University of Texas at Austin • Austin, TX 78712

I recently conducted an experiment by asking several colleagues at the University of Texas at Austin what words came to mind when they thought of Don Paul. For those who know him well, it is not surprising that the common descriptors included “smart,” “organized,” “honest,” “practical,” and “tough.”

While those five words undoubtedly capture his core personality, the word “productive” also pops to mind when I think of Don. By any standard, Don’s prodigious contributions to the chemical-engineering and materials-science literature place him almost in a class by himself. In addition to coauthoring over 450 archival journal articles and editing eight books, Don has also mentored 52 PhD students, 47 MS students, and 46 postdoctoral fellows during his career at Texas. Serving as the Editor-in-Chief of *Industrial and Engineering Chemistry Research* for fifteen years and being on the editorial boards of eight other journals has made his impact on the field of chemical engineering truly enormous.

Don’s research interests include the broad areas of polymer science and engineering and chemical engineering. His eight edited books cover a broad range of topics, but they have a common thread as a result of his interest in polymers.

Don’s current research involves polymer blends, mem-



branes for separations, drug delivery, packaging, and polymer processing. The blend research deals with the thermodynamics of polymer-polymer miscibility, phase diagrams and interfaces, reactive compatibilization of multiphase mixtures, rubber toughening, the control of phase morphology during processing by both chemical and physical means, and polymeric nanocomposites. His research on diffusion in polymers involves investigation of structure-property relationships to design better membranes for separation processes, improved barrier materials, physical aging of thin films, and “thermal switch” membranes.

Don has also contributed significantly to theories and models for describing sorption and permeation of small molecule penetrants in polymers. A broad range of materials, including rubbery, glassy, semicrystalline and liquid crystalline states of these materials, has been considered. Synthesis and characterization of novel materials is a key aspect of his work in all of the above sub-areas.

A BROAD ARRAY OF CONTRIBUTIONS

One of our departmental colleagues once joked that he held a still-unproven hypothesis that there are really identi-

cal twins with the initials DRP who operate from Don's office. While highly valuing productivity, Don's high standards for quality are also apparent, and his recognition as a creative and insightful investigator documents this aspect of his nature.

Beginning with the 1973 ACS Arthur Doolittle Award, a steady stream of honors bestowed on Don by colleagues underlines the respect in which his work is held by the chemistry and chemical engineering communities. In addition to the Doolittle Award, the ACS has recognized his contributions through the Phillips Award in Applied Polymer Science and the E.V. Murphree Award for Contributions to Industrial and Engineering Chemistry. The AIChE has recognized him with the Stine Materials Engineering and Science Award and the William H. Walker Award for Contributions to the Chemical Engineering Literature as well as by election as a Fellow.

He was elected to the National Academy of Engineering in 1988 for "outstanding research contributions on polymeric materials and for leadership in chemical engineering education." Don's Council of Chemical Research Malcom Pruitt Award and the Plastic Institute's Educational Service Award also emphasize not only his impact in scholarly publication and research arenas, but also his leadership at the interface between industry, government, and academia.

Don has presented numerous invited lectures, including the Warren McCabe lecture at North Carolina State University, the R.L. Pigford Memorial Lecture at the University of Delaware, the Ashton Hall Cary Lectures at Georgia Institute of Technology, and the Donald L. Katz Lecture at the University of Michigan. He has also served the chemical engineering community through his contributions to committees and organizations throughout his career. He was on the Education Projects Committee of the AIChE from 1968-77 and served as the editor for the *Chemical Engineering Faculties Directory* from 1967-77. He also was an ABET accreditation visitor from 1974-83. Don's ability to speak to both the chemistry and the chemical engineering communities is reflected by his active work with both the ACS and the AIChE.

Don served on the Executive Committee of the ACS Division of Polymeric Materials Sciences and Engineering from 1980-85 and in many capacities related to ACS publications well beyond his work as Editor in Chief of *I&EC Research*. His work on *I&EC Research* has seen close to 50,000 pages of archival journal pages published under his watch, with the collaborative assistance of many editorial colleagues, since 1986. His editorial contributions have also included service on editorial boards for *The Journal of Membrane Science*,

Polymer Engineering and Science, *Journal of Applied Polymer Science*, *Chemical Engineering Education*, *Polymer*, *Journal of Polymer Science*, *Polymer Physics*, *Polymer Contents*, and the Imperial College Press Series on Chemical Engineering.

Beyond the AIChE and ACS, Don has also been involved in activities of the Council of Chemical Research, serving on its Governing Board (1981-84) and its Executive Committee

[Don] published a classic paper regarding the mechanism of hydraulic permeability through membranes [that] helped call attention to the new program in polymers at UT and launched the membrane activities that have been a strong and continuous component of UT's graduate-studies area for over three decades.

(1983-84). He was a member of the Founding Committee of the North American Membrane Society. His work with the National Academy of Engineering has included service on the NAE Peer Committee in 1989-92 and 1994 as well as the Membership Committee from 1994-97. The National Research Council benefited from his input on its National Materials Advisory Board from 1988-94, its Committee on Polymer Science and Engineering from 1992-94, its U.S. National Committee on the International Union of Pure and Applied Chemistry from 1993-96, and its Solid State Science Committee from 1994-97. He also served on panels for Materials Science and Engineering at NIST and on the panel for International Benchmarking of U.S. Materials Science and Engineering Research.

Don's story begins in North Carolina where he grew up on a small farm near Washington, NC. He freely acknowledges the strong effect that this background has had on his lifestyle and motivation. An anecdote regarding this point is useful here. Don once told me that he recalls going out to hoe weeds out of a large field one hot North Carolina day. Looking at the very large and intimidating field, he decided not to think in terms of its size. Instead, he looked down the first row and thought, "I can get to the end of this one." Hoeing his way to the end of the row, he straightened up and looked down the next row, deciding "I can get to the end of this one, too." You can guess the rest—128 rows later he looked back on the entire field with a sense of accomplishment and an insight that has remained with him throughout the years. Whether it is writing papers or books, or educating nearly 150 graduate students and post docs, it is best to take it "one row at a time" and to just keep on working.

Don's contributions to teaching have also been widely recognized. He received the General Dynamics Teaching Award in 1977, which is the highest teaching recognition in the College of Engineering, and it focuses on contributions to undergraduate education. In 1994, our department nomi-

TABLE 1
Don Paul's Former Graduate Students

PhD Students

D.R. Kemp (1972)
C.E. Locke (1972)
O.M. Ebra-Lima (1973)
W.J. Koros (1977)
A.H. Chan (1978)
C.A. Cruz Ramos (1978)
J.E. Harris (1981)
R.S. Barnum (1981)
E. Woo (1984)
J.-S. Chiou (1985)
Y. Maeda (1985)
A.C. Fernandes (1986)
M.J. El-Hibri (1986)
T.A. Barbari (1986)
M.E. Fowler (1987)
N. Muruganandam (1987)
M.C. Schwarz (1987)
C.-H. Lai (1988)
P.S. Tucker (1988)
A.C. Puleo (1988)
J.H. Kim (1989)
P.C. Raymond (1989)
J.M. Mohr (1990)
J.S. McHattie (1990)
H. Kim (1990)
G.R. Brannock (1990)
T.-W. Cheng (1991)
I. Park (1991)
D.H. Weinkauff (1991)
Y. Takeda (1992)
C.L. Aitken (1992)
C.K. Kim (1992)
T.A. Callaghan (1992)
M. Aguilar-Vega (1993)
J.D. Le Roux (1993)
M. Nishimoto (1994)
P.P. Gan (1994)
B. Majumdar (1994)
A.G. Gonzalez (1995)
M.R. Pixton (1995)
M. Lu (1995)
A.J. Oshinski (1995)
S. Ziaee (1995)
K.A. Schult (1996)
C.T. Wright (1997)
F.A. Ruiz-Trevino (1997)
G.S. Wildes (1998)
W.R. Hale (1998)
M.S. McCaig (1998)
G.D. Merfeld (1998)
R.A. Kudva (1999)
J. H.-C. Chu (1999)
Z. Mogri (2001)

MS Students

D.R. Kemp (1969)
J.H. Troell (1969)
O.M. Ebra-Lima (1970)
J. St. Lawrence (1970)
V. Mavichak (1970)
C.E. Vinson (1971)
D.H. Carranza (1972)
A.E. Mann (1972)
R.E. Robertson (1972)
M. Garcin (1973)
J.O. Altamirano (1974)
J.R. Stell (1974)
J.D. Paciotti (1974)
A.A. Rocha (1974)
W.E. Garmon (1975)
R.L. Imken (1975)
S. McSpadden (1975)
A.J. Meyer (1975)
D. Wahrmund (1975)
T.R. Nassar (1976)
R.N. Mohn (1977)
R.E. Bernstein (1977)
J.C. Tiffany (1978)
G. Wonders (1978)
E. Nolley (1978)
A.J. Erb (1979)
D.W. Bartlett (1979)
C.R. Lindsey (1979)
P.-T. Chang (1980)
M.D. Lorenz (1980)
J.J. Ziska (1980)
P. Masi (1980)
E.A. Joseph (1981)
W.A. Smith (1981)
E.Y. Adham (1982)
T.D. Traugott (1982)
W.E. Preston (1982)
S.R. Murff (1983)
J.D. Keitz (1983)
C. McCutcheon (1983)
J.-L. G. Pfennig (1984)
V.J. Triacca (1989)
G.P. Shaver (1989)
J. Oshinski (1990)
A.B. Lombardo (1994)
S. Gupta (1995)
A. Kelkar (2000)

nated Don for the University-wide Graduate Teaching Award. We contacted his former graduate students for possible letters of support. The response was overwhelming. Letters poured in from all over, since by that time Don's former students had achieved distinguished positions in many parts of the world. The recurring theme of these letters was an expression of the writer's feelings of deep appreciation for Don's help in their educational development by his tough, but ultimately compassionate, mentorship. As one of these former students, I was more than pleased that Don received this highly competitive award in recognition of his educational efforts.

Don's BS in chemical engineering was earned at North Carolina State University (1961) and his graduate work was carried out at the University of Wisconsin, Madison (1965). He has been recognized by both of his alma maters with distinguished graduate awards.

In addition to summer work at DuPont in the nonwoven fabric area in 1960-61, Don was a Research Chemical Engineer at Chemstrand Research Center in North Carolina's Research Triangle Park from 1965 to 1967.

LIFE AND LEADERSHIP IN THE DEPARTMENT

Don joined the University of Texas faculty in 1967 and has been here now for 34 years. Progressing through the ranks to Associate Professor in 1970 and to Full Professor in 1973, he took an early role as a departmental leader. He served as the department's Associate Chairman from 1973-77 and as its Chairman from 1977-85. During his Chairmanship, Don recognized the need for a forward-looking approach. He assembled a committee comprised of distinguished leaders in the chemical and petrochemical industries as well as from the academic community to evaluate the curriculum. The committee also analyzed the future needs of the department and the larger chemical engineering community. Many of the elements of this visionary plan are still used as the guiding principles for our department.

One of Don's favorite statements is that "chemical engineering is defined by what chemical engineers do." That attitude helped position the department as an early player in the polymer, materials science, microelectronic, and biotechnology opportunities that have helped maintain the vitality of our discipline.

Don was also quick to see the need for better bricks, mortar, and laboratory facilities to allow the department's movement toward the new technological areas, while still maintaining connections to its petrochemical roots. He was a key person in acquiring the needed resources to construct our current modern facility, which was occupied in 1986 at the end of his term as Chairman. Strong connections with our alumni and industrial friends also led to the establishment of a large number of endowed positions in the department and college during this period. Don himself was selected as the T. Brockett Hudson Professor in 1978 and as the Melvin H. Gertz Regents Chair in Chemical Engineering in 1985.

Following his term as Chairman, Don returned to his active research and teaching duties in the department and served as a mentor for several faculty who were at the time making the transition to academia from industry. During the time he served as Chairman, he managed to maintain an energetic research program, but when he stepped down from that

position, a literal explosion of activity became apparent through his PhD supervision and his publications.

MAJOR TECHNICAL CONTRIBUTIONS

Don's interests and contributions in polymer engineering and science have included work in both polymer blends and membranes. Not surprisingly, he has managed to also combine his insights in these two separate areas to provide important contributions in advanced blend membrane systems for gas separation membranes.

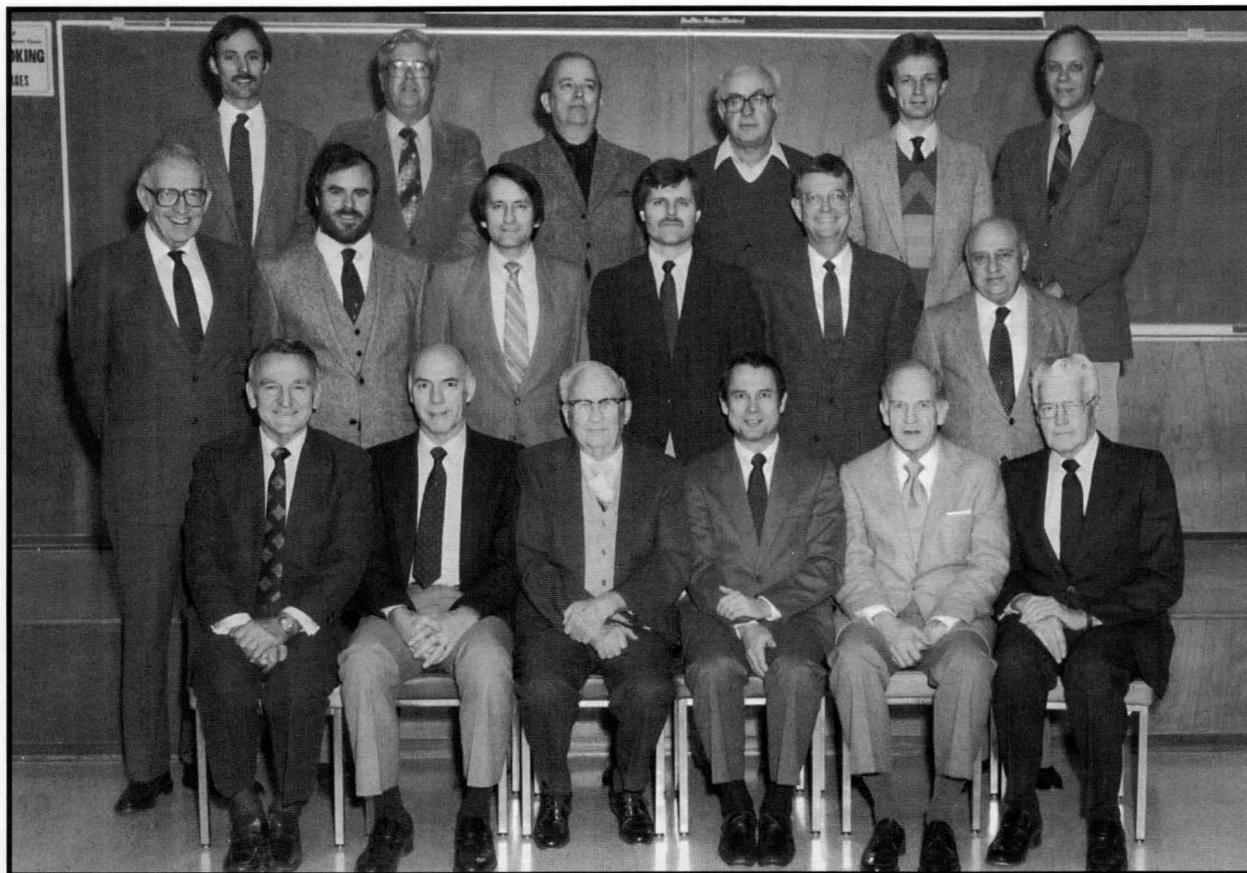
Don's work in polymer blends has led to an important route to new commercial polymer products. His work has integrated thermodynamics, interfacial phenomena, rheology, process, morphology, and properties of these novel materials to provide a solid scientific foundation for this field. Since the late 1940s, numerous papers have suggested that polymer-polymer mixtures were unlikely to be miscible. This belief discouraged and delayed the development of any widespread interest in blends. Indeed, the favorable entropy of mixing for two polymers was known to be very small, if not

entirely negligible. Moreover, the premise at the time was that enthalpic effects were positive and unfavorable for mixing.

Don was a pioneer in focusing attention on polymer-polymer interactions as the key to developing miscible blends. He and his colleague, Joel Barlow, published an important paper showing that intramolecular repulsive interactions in random copolymers can provide the basis for exothermic mixing, thereby promoting miscibility with other polymers. This effect meant that such random copolymers could form miscible blends, even when the corresponding homopolymers could not. This non-intuitive concept was simultaneously recognized by two other groups and is now a cornerstone of polymer-blend technology.

In 1992, Don and his students initiated a series of papers that combined this copolymer model with a modern equation-of-state theory of mixing. Their work allowed a matrix of interaction energies to be constructed to predict the miscibility of multiple polymers and to design copolymers for controlled phase behavior in blends.

This work is also useful for understanding and designing



UT's chemical engineering faculty at the time of Don's Chairmanship in 1984. **Top row:** Keith P. Johnston, E.T. Beynon, James R. Brock, Hugo Steinfink, Douglas R. Lloyd, Joel W. Barlow. **Middle row:** James R. Fair, Thomas F. Edgar, Gary T. Rochelle, John G. Ekerdt, James E. Stice, Herbert Grove. **Seated:** John J. McKetta, Eugene H. Wissler, William A. Cunningham, Donald R. Paul, Howard F. Rase, Joel Hougen. (Missing: David M. Himmelblau, W.J. Koros, R.P. Popovich, and R.S. Schechter)

phase-separated (immiscible) blends in which polymer-polymer interactions are manifested in the nature of the interface between the phases. Don's work in this area has been commercialized through long-standing collaborations with various companies.

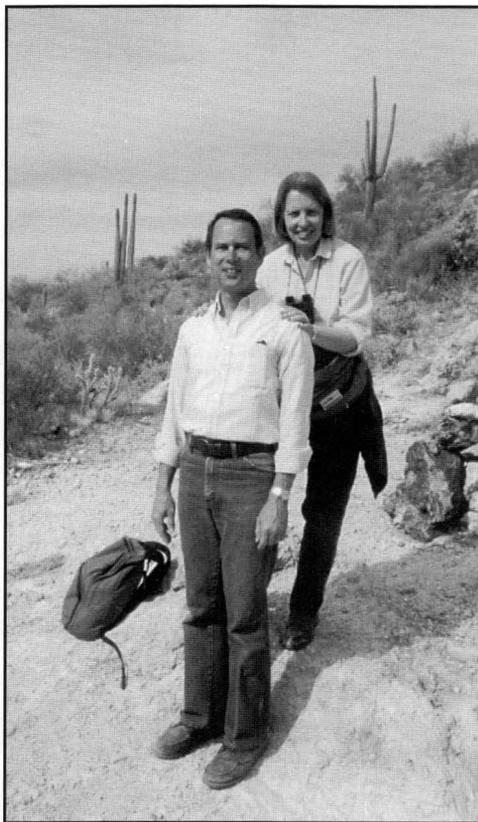
In addition to the enormous amount of work in polymer blends, Don has pioneered the development of membranes. Within his first year as an Assistant Professor at Texas, he published a classic paper regarding the mechanism of hydraulic permeability through membranes. This paper helped call attention to the new program in polymers at UT and launched the membrane activities that have been a strong and continuous component of UT's graduate-studies area for over three decades. Soon after completing this paper on liquid permeation, he published a second classic analysis of membranes—this one related to gas transport in glassy polymers. Don cooperated with the group at Monsanto that developed the first truly commercially successful gas separation membrane system, called "Prism."

Over the intervening years, Don and his co-workers have systematically studied the relationship between polymer structure and the gas permeation properties of novel materials synthesized in their labs. Important principles of molecular design have emerged from his work. These insights have been codified into a group contribution scheme for predicting membrane performance. Several new materials of significant commercial interest have been identified. Moreover, novel processing schemes involving flourination, crosslinking (and of course, blending) of polymers and low-molecular-weight compounds have been studied.

FAMILY

The only commitment that exceeds in length Don's association with the UT department is the one with his extraordinary wife, Sally. Don and Sally met while in graduate school at Wisconsin in 1963. Her disposition and nature caused her to take an interest in children with special needs. Completing her Masters in Speech Therapy meshed well with the timing of Don's completion of his PhD, and they celebrated by getting married in 1964. After locating in Austin, they raised a family that includes Mark, a master pastry chef trained at the James Beard School in New York City, and Ann, who is currently an auditor with the State of Texas.

Over the years, Don and Sally shared another favorite



Don and Sally on a hiking trip.

activity—hiking. In addition to hiking, boating, and other outdoor pursuits, Don has a great love of cooking and a passion for music, especially jazz and blues. His music collection is of such a size that only someone with his organization skill could maintain it in functional form.

In 1995, the saddest event in Don's life removed Sally from him and his children. Her death led to a period of deep mourning that eventually yielded to the tough nature that, as noted in the introduction, is one of Don's signature qualities.

THE RECENT PAST AND THE FUTURE

I recall having lunch with Don eighteen months after Sally's death. He had his old spark back and told me that he wanted to do something significant for the institution that had helped him so much. He said he had been thinking about the lack of a formal Materials Science Department at UT and how this was often cited as a

problem that needed to be dealt with. He said, "I now see this as a possible advantage, rather than a disadvantage, if it is handled properly." He unveiled an idea for a materials institute that would cut across college as well as departmental boundaries.

Don visualized a network of individuals linked together by their common interest in materials and with a core of instruments and facilities in a central institute. His vision quickly spread beyond lunchtime conversation to the offices of deans and the vice president of research. With the valuable support of the administration, Don's concept moved toward reality.

At this point, Don's "take-one-row-at-a-time" approach resurfaced. He made the rounds from the physics department to the chemistry department to the aerospace, chemical, electrical, and mechanical engineering departments, recruiting support at the grass-roots level to match the upper-administration support. In 1998, the Texas Materials Institute became a reality, and Don was inducted as its first director. Under his leadership, materials work is now prospering at UT. New facilities, new positions in various departments, and colleagueships that would probably not have occurred have begun—one row at a time. Our colleagues in the department, in the college, and across the university appreciate and value Don's catalytic contribution in fostering this unusual and valuable addition to our university. We are all indebted to Don for his uniquely broad and deep contributions. □

Elementary Principles of Chemical Processes

3rd Edition

By Richard M. Felder and Ronald W. Rousseau

John Wiley & Sons, 605 Third Avenue, New York, NY 10158-0012; 675+ pages; \$111.95 (cloth); (2000)

Reviewed by

D. Hunkeler

Swiss Federal Institute of Technology

The third edition of this classic introductory chemical engineering text is intended to compliment a first course in stoichiometry, material and energy balances, and introductory thermodynamics. As such, it is aimed at engineering and chemistry students who have completed their first year of general university education. Freshman physics and chemistry are valid prerequisites, although if the course is taught with the complimentary teaching modules, one could consider offering it earlier. The third edition follows the same format as the previous two editions, with a preliminary set of three chapters discussing the units and dimensioning of process variables and their associated calculations. This section is (in some curricula) omitted, due to its coverage in other courses, but it is a valuable asset since many student difficulties in balances occur due to sloppy "accounting."

The body of the text discusses material balances, first for non-reactive single-phase processes and then adding multiphase systems, recycling, and bypass. One of the strengths of the book is the ease with which the authors' introduce thermodynamics into the subject matter. Equations of state for non-ideal gases, compressibility, multicomponent equilibrium, and two-phase partitioning and solid-liquid-vapor phase diagrams are presented in a comprehensible manner that permits students to begin solving problems on the day of the lecture. This is something Felder has long advocated in his interactive teaching approaches, and the third edition certainly shows the value of the NSF's sponsoring of the concepts which brought it to fruition.

The text also integrates graphical presentations of correlations with computer-based programming challenges. The students will not realize until subsequent courses, to what extent they have been introduced to (and to a large extent mastered) elementary chemical and engineering thermodynamics. The problems at the end of the chapter do an excellent job of integrating the concepts presented, along with statistics, into the estimation of thermodynamic data.

Practical problems, related to a series of important unit operations including various separation methods such as absorption, adsorption, condensation, crystallization, distillation, and extraction are presented throughout the first eleven chapters. The authors' also discuss batch, semi-batch, and

continuous reactors operating under adiabatic and isothermal conditions, both at steady state and dynamically. Combustion is treated separately. Liquid-gas processes including evaporation-compression, humidification, dehumidification, and scrubbing are also integrated into material and energy balances. Overall, the new problems are challenging, yet doable.

The third section of the book discusses energy and energy balances. There is minimal overlap with the discussion of forms of energy typically presented in freshman physics. Energy balances on non-reactive processes challenge students to organize their solutions. The text pulls itself together in Chapter 9 when the enthalpy of reaction is used, and estimated, principally to permit the calculation of a reactor's energy loss, temperature, or pressure. The balances are also extended to complete processes. Discussions of alternative fuels, which may appear old-fashioned, is a take-home deliverable from this text, as are its extensive data base (tables, graphs, and CDs) that may convince sophomores they never have to set foot in an engineering library.

The text concludes with a chapter on computer-aided calculations, which many schools cover in a separate course (as they do the material on transient processes). But if Chapters 10 and 11 are omitted, Chapters 12 through 14 cannot be. The authors' offer three case studies (one in the area of materials and two in commodity chemistry) that need to be presented at the end of the two-semester sequence to convince students they can, indeed, design plants. It is a motivation which will drive many of them to integrate kinetics, reactor design, transport phenomena, and separations into their working knowledge and become chemical engineers. As the only chemical engineering course taught to chemists, in my experience, it provides an excellent sensitization to the challenges facing industrial organic and polymer chemists when they develop new (macro) molecules.

The text comes with a CD that includes an animated encyclopedia of chemical process equipment, the E-Z solve software for balances along with tutorials, and an index of learning styles. As fantastic as these are, the real value is that the physical property database demystifies the coupling between thermodynamics and engineering, which confuses so many students. With the database provided, carrying out material balances is no longer a cumbersome task akin to financial accounting, but is fun. Felder and Rousseau have made chemical engineering enjoyable. My students make significantly less calculation errors on their balances thanks to the third edition of this book, and they are motivated and listen better to the concepts their predecessors had ignored.

Overall, the authors' present a way for introductory students to respect complexity and understand the need for engineering approximations. Take the authors' advice to let the students enjoy problem-based learning—they will better understand themselves, their career, and their choices. The book is a service to our profession. □

EFFICIENT, EFFECTIVE TEACHING

PHILLIP C. WANKAT

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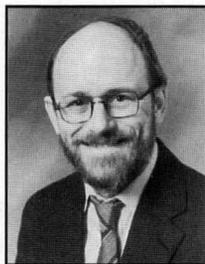
Good teaching requires that students must learn the right content, have a good attitude, and learn how-to-learn. Teaching is efficient for students when there is a high ratio of (student learning)/(student time on the course). Because they are so busy, professors also benefit from courses that are reasonably efficient. A course is efficient for professors when there is a high ratio of (student learning)/(professor's time on the course). Although there are times when effective teaching and efficient teaching conflict, most of the time effective teaching can also be efficient.

As a professor, you can apply the techniques of time management and efficiency by becoming familiar with concepts such as missions, goals, priorities, to-do lists, calendars, and prime time.^[1,2] These methods should be applied,^[3] paying special attention to efficient teaching.^[3-6]

EFFICIENT TEACHING OF LECTURE COURSES^[3]

Course Development

Designing a course is basically an engineering design problem. What is the purpose of the course? The purpose of a required undergraduate course is obviously very different than the purpose of an elective. You should obtain several old outlines and syllabi. Talk both to professors who have



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taught the course and to those who teach prerequisite courses to see what you can expect the students to know. Talk to professors who teach follow-up courses to determine what students must learn in your course.

The syllabus is a contract with the students. Find a good one and adapt it with appropriate modifications for your course. Be explicit about rules and regulations. The students will not know what you expect of them until you tell them (even then some students will claim ignorance). Start with firm, and perhaps even tough, rules—then relax later on. As part of the syllabus, you should develop a tentative course outline. Plan to spend one or two periods at the beginning of the semester reviewing material the students are supposed to know, and plan one period before every major test for catch-up and review. Cover less, but cover it in more depth than was previously done. Many students only work when there are assignments or tests, so there should be something for the students to do outside of class at least every other week, preferably more often.

Shortly after the first test, ask for feedback from the students, using a “one-minute quiz.” Pass out index cards and ask students what you (and the TAs) can do to help them learn more. Using the responses you receive, make appropriate changes to improve the course. Midcourse corrections based on this feedback can rescue a course headed for disaster. Allowing students to have input into test dates and due dates of projects also indicates your willingness to listen—and will be greatly appreciated by your students.

Finally, arrange to teach the same course three or four times in succession. This allows you to reuse much of your preparation and results in a better course in less time. At the end of the semester reflectively analyze what worked and what didn't, then plan changes for the next offering while the details of the course are still fresh in your mind.

Lectures

Lecturing is the most efficient teaching method the first time a course is taught. Since lectures can be prepared immediately before class, it is easy to adjust the course as you proceed through the semester. Lectures must actively engage the students in order to be effective. In subsequent offerings of the course, try modifying the lecture approach or try other teaching approaches such as cooperative group techniques.

When you know the material, you can prepare a new fifty-minute lecture in two hours or less. Repeat lectures can be prepared in one-half hour. Trying to prepare a lecture in less time is obviously dangerous. Unfortunately, many new faculty spend significantly more time than this without becoming good teachers.^[5,6] Spend the two hours of preparation time in several short bursts, starting at least a day before the lecture will be delivered. The first fifteen minutes of preparation should be used to develop a title and a brief conceptual outline. Fill in some of the details later, but do not write out your notes word-for-word.

Since a student's maximum attention span is 15 to 20 minutes, the standard fifty-minute lecture hour should have one or two lecture breaks to make it effective. For example, a good scheduling might be

- *Introduction and short review*
- *Mini-lecture*
- *Lecture break*
- *Mini-lecture*
- *Summary and transition to homework for next class*

Good lecture breaks include active learning exercises such as small-group discussion, small-group problem solving, brainstorming, and student reflection. Since the audience's limited attention span forces you to use breaks, you will naturally cover less material; but the breaks serve to refresh the students so they pay more attention to the mini-lectures, and the in-depth processing that occurs during breaks increases student learning.

With a little practice it is possible to be comfortable lecturing and to actually enjoy it. If you are uncomfortable the students will be uncomfortable, regardless of how well-prepared you are. Quickly prepared, brief lecture notes are effective since they control content tyranny. By focusing on the most important points and leaving details to examples, you don't have to race through every second of the lecture. Remember that from the students' viewpoint, it is more important to end on time than to cover everything.

The second time you teach the course, try making partial lecture transparencies. Include most of the material needed for the transparency, but skip some of the key points. Give copies of these notes to the students. This procedure will eliminate many of the errors inherent in note taking and will

give the students time to think—but it will still require them to pay attention so they can fill in the key missing items. You can thus cover more material without sacrificing student understanding.

Tests

Write new tests every term. As you teach, create a file of possible test problems. They can be variants of homework problems, or problems sparked by student misunderstandings, and so forth. The purpose of the file is to provide potential problems that can be considered when you write the test. Avoid disasters by solving the test completely before using it, and record how long it takes you to solve the test. Freshmen and sophomores will need about five times as long, juniors about four times as long, and seniors about three times as long.

Discussing procedures in class thoroughly before the first test will help reduce the students' anxiety. A good practice is to use old tests as ungraded practice tests that the students can do on their own, posting the solution on a bulletin board or on the web. This access to old tests helps greatly in reducing student test anxiety. Be present for the test since you are the best one to fix any last-minute errors or problems. There is also less cheating when the professor is present. If at least half the class is unable to finish the test on time, the test is too long.

Try to make grading as fair as possible, keeping in mind that students consider unfair grading to be unethical. For reasons of consistency, prepare a solution key to allocate partial credit when appropriate. Fair grading requires a regrade procedure. Reduce the hassle of regrades by requiring written regrade requests.

Attention to Students

Students want and deserve individual attention. They are very tolerant of fumbling in the lecture if they believe you care about them. Although the average engineering undergraduate may not be as smart as your peers in graduate school were, remember that he or she counts among the best undergraduates at your school. And sheer technical competence is less important for success in industry than motivation, hard work, timing (or luck), communication skills, and the ability to work well with a diverse assortment of people. Look for the best in your students, and you will probably find it—professors with a good attitude usually end up with students with good attitudes.

If you don't learn the students' names, they will feel like just numbers on a list and will be much more likely to skip class, be disruptive, not do the work, and/or cheat. Admittedly, learning a lot of new names each semester is difficult, but the effort is repaid by smoother course operation. Any-

thing you know beyond their names, such as hometowns or career goals, will greatly help you gain rapport with them.

Since personal attention to the students' needs requires a significant expenditure of time, efficiency and effectiveness can get lost in the competition for their share of time. A reasonable compromise is to hold scheduled group help sessions (particularly before tests) and a modest number of scheduled office hours during the week. Be available to the students during your office hours. Also, asking your teaching assistants to hold office hours provides another opportunity for the students to learn.

Come to class five minutes early and stay five minutes after class. In addition to giving you a chance to prepare the classroom, coming early sends the message to the students that you are looking forward to this class. Staying late offers a good time to answer questions. The combination of coming early and staying late provides an opportunity for individual attention, particularly for those students who will not use office hours.

When students ask for special arrangements to take tests or to turn in homework, be flexible, but require them to be responsible and to inform you in advance if possible. Occasionally students will abuse your generosity. It will usually be clear when this has happened, however, and you should make sure it does not happen a second time. If you treat students as adults, most of them will act accordingly.

A NEW TEACHING-LEARNING PARADIGM

Standard courses use a teacher-centered paradigm. Even when such courses are well taught, using advanced strategies such as cooperative groups, they suffer from some deficiencies that appear to be inherent to the basic paradigm. Students seldom learn how-to-learn on their own and there is a clear limit to the professor's efficiency in teaching the course. Relatively mature students can take more responsibility for their learning and be taught with a problem- or project-centered paradigm.

Engineering students will focus on learning when there is a task that must be completed. Problem-based learning^[7] (PBL) is a method for using problems or short projects to focus student attention on learning. While PBL does help students learn how-to-learn, it does not increase the professor's efficiency since preparation and grading of the projects is very time-consuming. PBL is usually reported as increasing, not decreasing, the time the professor spends on the course. For students to learn how-to-learn and to drastically increase the professor's efficiency while retaining course effectiveness, a different paradigm is needed.

Fortunately, the efficiency literature gives us a clue as to what this paradigm should include—delegation.^[1,2] Instead of the professor planning the material, picking topics, preparing material, lecturing, etc., ask the students do this work.

With appropriate feedback from the professor, delegation of these responsibilities to the students can result in significant growth in their ability to learn. Delegation can be used for the entire course^[8] or for a portion of the course.

Course projects are an effective way to focus students' attention, and they lend themselves to delegation of responsibilities. Projects lead to more learning if significant class time is devoted to them. For example, finish the lecture portion of the class before the end of the term and spend the remaining class time on project work. If class time is not devoted to the project, students consider it add-on work. Although projects can be done by individuals or groups, group projects result in much more significant efforts. I assign the groups to ensure that they are diverse in ability, learning styles, and work styles. Use the principles of good cooperative group instruction.^[4]

The professor sets the tone for the project work. Expect graduate students and seniors to deliver professional quality work. Provide examples of papers or reports that surpass the minimal quality standards. Give guidelines for topics and some examples, but expect the students to devise their own topics and titles. Work with the students to narrow the scope of their projects so that they can be finished in the time available. For example, one group that started with the topic of supercritical extraction had 19,000 hits in a computerized search. Two iterations later, the topic supercritical extraction of coffee resulted in 65 hits, which is a much more manageable number. The topic must be something new for the students. Do not allow recycling of projects from other courses and note in writing that recycling projects will be considered a form of cheating. Although allowing students to do a project on their master's or PhD research might seem efficient, it is unfair to students who are not doing research in an area related to the course.

Regular meetings with groups during scheduled class time and periodic student presentations to the entire class help combat procrastination. Final reports will be significantly better if students first turn in a rough draft. Have another group critique each rough report. These critiques help to improve the final reports and give the students practice in the highest level of Bloom's taxonomy—evaluation. If the critiques are graded, the students will take this exercise seriously. I also critique the drafts with the idea of showing the groups areas for improvement. Allow about one week for groups to finish their reports after the critiques are returned. I also ask the students to fill out forms to critique oral presentations, but these critiques are not graded. A side benefit of requiring critiques is that everyone pays attention and learns from the projects of all groups.

Weekly group meetings instead of lectures help prevent procrastination, keep the professor informed of group progress, and provide an inkling of personal interactions within each group. In addition to commenting on the techni-

cal work, take time to discuss work habits when necessary. For example, most graduate students have not learned how to rapidly sort articles so that only the most important are read thoroughly. The professor can also be a cheerleader when groups feel that they will never be able to finish their projects. When the members of a group are not getting along, part of the meeting time can be used to help the students start processing group interactions. Do not try to solve their interpersonal problems, however. Make the students do this work or at least muddle through it.

The bane of grading group work is freeloaders. Delegate the responsibility of lowering the grades of freeloaders to the students. My grade assigned to each project is the highest grade students in the group can receive for the project. I require the students in each group to assign what percentage of this grade (ranging from 0 to 100%) each group member should receive. I then average these percentages for each group member and calculate their project grades. This procedure reduces freeloading and drastically reduces complaints from other group members when freeloading occurs.

This project-based paradigm is very efficient for professors. During the project work I typically spend a total of four hours per week on the course, with most of that time focused on the students. During project work the students spend much more time working on the course than the professor does!

Grading reports takes time, but since the reports are better than in other classes it is easier. The students learn their topic in depth, they learn how-to-learn, and they actually pay attention to the feedback on their writing.

A note of caution is in order, however. Most professors and students are inexperienced with project-based teaching. Professors need a certain amount of chutzpah to relinquish the normal control of a lecture course. They also need to know the material better than they would for a lecture class since it is impossible to prepare for student questions. Note that this method is not "turning the students loose." Students actually receive increased guidance and support. Despite the support, the freedom and responsibility may overwhelm immature students. Students, particularly those with high grades, may rebel. Other faculty may be skeptical and probably will not be supportive if the course flounders. Because of these risks, a graduate- or senior-level elective course is a good place to experiment.

IMPROVEMENT AND GROWTH

Master teachers may be born, not made; but good, efficient teaching is a learned skill. Sign up for a teaching workshop. Study and try out new teaching methods. After each class, reflect on what worked and what didn't, and tailor your future actions accordingly. Take notes, with the aim of improving the course next time. Find someone in your department with whom you can discuss teaching on a

regular basis. Continual experimentation with teaching methods helps to prevent boredom and burnout, which can be major problems. Such experimentation can lead to teaching improvement and eventual recognition as a master teacher.

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ChE book review

Multimedia Fluid Mechanics

by G.M. Homsy, *et al.*

Cambridge University Press (2000) \$19.95

Reviewed by

Hossein Haj-Hariri

University of Virginia

The CD by Homsy, *et al.*, is a most welcome and timely educational tool for students (and instructors!) of introductory fluid mechanics. Fluid mechanics is a very visual discipline. To date, such visual accompaniment to the mathematical equations describing flow physics has either come from labs or from samplings of the fantastic movies put together in the 1960s. Whereas the material of those movies will never become outdated, the innovative multi-media approach adopted by Homsy, *et al.*, adds dimensions to the presentation that were simply not available forty years ago. This CD ROM is a true multi-media tool that has no paper counterpart. In other words, this is not a book typed on a CD—it is truly all that the box cover promises, and then some.

The approach is based on modules. Currently, there are three technical modules, with more promised. The current modules are dynamics, kinematics, and boundary layers. There is also a module on history, which should be studied by all students.

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A SUPERCRITICAL EXTRACTION EXPERIMENT

For the Unit Operations Laboratory

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Supercritical fluid extraction (SCFE) is becoming a viable unit operation in the chemical process industry. It uses the distinguishing properties of a fluid that is above its critical point (critical temperature and pressure) to enhance performance in an extraction process. While the concept of SCFE has been known for over a century,^[1] it has not been widely used in industry for a variety of reasons. Foremost among these reasons is the high financial risk involved with SCFE—specifically, high installation and operating costs for a process with a relatively short track record of commercial-scale success. Another reason is that a conventional separation technique is usually already available. Add to this the difficulties caused by the lack of sound theoretical models available for scale-up and it becomes obvious why there has been no incentive for SCFE development on a wide-scale industrial level. Even the early commercial applications, such as propane deasphalting in the 1930s, the SOLEXOL process of the 1940s, and the ROSE process in the 1950s, were not enough to generate large-scale interest.^[2]

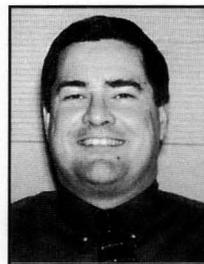
While these reasons remain true today, new motivating factors have recently paved the way for SCFE to become a viable extraction alternative. The modern chemical engineer is faced with environmental regulations that require strict control of emissions and reductions in hazardous waste. A change in energy costs has lessened the favorable gap in operating costs conventional high-heat separation techniques such as distillation have historically had over high-pressure SCFE systems. Increased performance demands, such as lower acceptable limits of either residual solvent or other contaminants in the food and pharmaceutical industries, have increased the popularity of SCFE. Also, SCFE solvents (such

as carbon dioxide) are often more environmentally friendly.

As SCFE becomes more and more popular in industry, it is finding widespread applications from the decaffeination of coffee to the removal of trace organic contaminants in waste water.^[3] Additional work is going on in many other areas from coal liquefaction^[4] to fractionation and purification of polymers.^[5] Some of these processes (such as coffee decaffeination) are vastly different from the original deasphalting and ROSE processes, while others (such as coal liquefaction) are very similar. While these widely varying applications are using many different solvents, the one used most predominantly is carbon dioxide.

Supercritical fluid extraction also presents a unique combination of high-pressure phase equilibrium and mass transfer. As such, an experiment dealing with SCFE represents a

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... this article discusses a laboratory experiment that both reinforces fundamental engineering principles and introduces the students to one segment of this growing technology—specifically solid/SCFE.

valuable addition to the traditional unit operations laboratory. With that in mind, this article discusses a laboratory experiment that both reinforces fundamental engineering principles and introduces the students to one segment of this growing technology—specifically solid/SCFE.

The experiment provides an opportunity for the students to explore SCFE and to use their engineering skills to deal with issues of scale-up and high-pressure equipment design and operation.^[6] From a thermodynamic point of view, it allows students to explore physical-property prediction at high pressures far away from ideal behavior when experimental data are not available. They are then asked to use these predictions to correlate an equipment design parameter such as the mass transfer coefficient. Additionally, students have the opportunity to evaluate the usefulness of the data they have collected. They will need to understand that if the data indicates saturation of the exit stream, their analysis of the mass transfer coefficient will be invalid because the equation they are using (see Eq. 1 in the “Analysis” section) becomes indeterminate. Finally, they will need to have developed a plan to avoid saturation prior to starting the experiment in order to be successful.

As far as we know, the inclusion of a supercritical extraction experiment in the senior unit operations laboratory is unique.

STUDENT EXPERIMENT

The experiment consists of a semi-continuous packed-bed extraction of naphthalene by supercritical carbon dioxide. The primary objective is to measure the mass transfer coefficient for the extraction at a variety of conditions and to develop a correlation for it as a function of these process conditions. Carbon dioxide was the chosen solvent because of its moderate critical conditions (304.2 K, 73.8 bar), its widespread industrial use, and its environmentally friendly nature. It is also nontoxic, making it a very safe lab solvent. Naphthalene was chosen because of its relatively high solubility in supercritical carbon dioxide and the availability of sufficient data on the system.^[5]

Equipment

The experiment consists primarily of a supercritical screening system (see Figure 1) designed and manufactured by Autoclave Engineers of Erie, Pennsylvania. The pre-as-

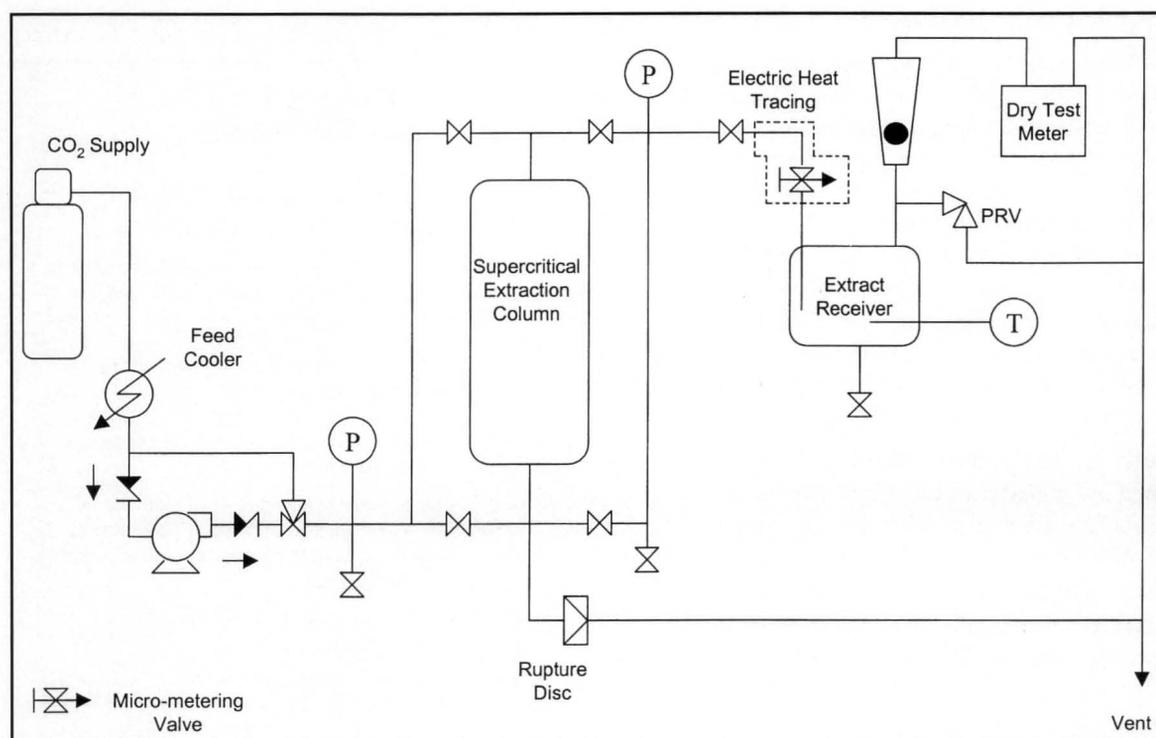


Figure 1.

Flow diagram: supercritical fluid extraction system.

sembled system includes all the necessary basic components: feed pump, extraction column, extract receiver, instrumentation, and a heated pressure boundary used to depressurize the exit stream. The cost of an Autoclave (814-838-5700) system typical of the one used in this laboratory was slightly lower than a similar system made by ISCO (800-228-4250). The heated pressure boundary was optional and added to the cost of the ISCO SCF 1200 system. One additional benefit of the Autoclave system is that it is a little larger in size than the ISCO system. Since this is intended to be a unit operations laboratory, we felt that having an analytical-scale unit would not do justice to the concept of SCFE as a unit operation. We wanted the students to have some degree of a “hands-on” experience with the lab that we felt would not be achieved with smaller analytical-scale equipment.

A standard CO₂ cylinder with a liquid dip tube is used as the feed tank. The CO₂ is cooled by passing the feed tube through an ice bath prior to entering a Milton Roy 1/4-Hp, variable-speed positive-displacement (PD) pump. The PD pump is capable of operating between 40–400 cc/hr. The pump discharge pressure is controlled by an adjustable back-pressure control valve that can operate in the range of 8–480 bar. Excess flow, which causes a pressure higher than the desired set point, is recirculated back to the suction side of the pump. The pump discharge pressure is measured just upstream of this control valve. A vapor vent valve is supplied downstream of the back-pressure control valve. This allows any vaporized CO₂ caught in the pump feed line to be vented off during start-up. Without the vent, the feed pump would become vapor bound and cavitate. Additional cooling is obtained by packing the pump head in ice.

Four valves around the extraction column isolate the column and provide the flexibility needed to operate it in either an upflow or downflow configuration. The column is 12 inches long, has an inside diameter of 0.688 inches (nominal 1 inch OD), and is rated for approximately 700 bar at 100°C. It can be electrically heated with two external band heaters. A surface-mounted thermocouple measures the outer column wall temperature, and a Watlow proportional/integral controller is used to control the temperature. The column is protected from overpressurization by a 1/4-inch diameter rupture disc that is piped directly to the bottom of the column. The disc is nominally rated for 480 bar at 22°C.

The pressure boundary on the downstream side of the column is maintained by a micro-metering needle valve, also supplied by Autoclave Engineers. The column can be isolated upstream of this valve with a blocking valve. The discharge lines from the column, as well as the body of the micro-metering valve, are electrically heat traced with a 110-volt heating tape. The heat tracing is in place to counteract the large Joule-Thomson cooling effect that results when the CO₂ flashes across the micro-metering valve and to

prevent the line from freezing.

The extracted material is collected in the extract receiver. This vessel has a nominal volume of 99 cubic centimeters and has a drain valve at the bottom. The vessel is protected by a pressure relief valve set to open at 1.4 bar (at 22°C). The extract and solvent enter the receiver from the top. The extract, which is no longer soluble in the non-supercritical solvent, separates from the solvent and is collected in the vessel while the solute-free CO₂ is discharged from the top of the vessel. It then passes through a small filter to a rotameter and then through the dry test meter. In addition, the temperature in the extract receiver is measured by a thermocouple. The rotameter (calibrated for CO₂ at standard temperature and pressure in units of standard cubic feet per minute) measures the instantaneous CO₂ flow rate. The CO₂ flow is then totalized by a dry test meter. This provides total standard cubic feet of CO₂ used during an experiment.

Procedure

The students are provided with the equipment, and are given detailed safety instructions and a list of “Discussion Topics” (see Table 1). Additionally, the experiment is conducted under closer-than-normal supervision for the senior unit operations lab. The students must develop their own experimental plan that will allow them to answer the questions outlined in the discussion topics. In developing their plan, they must decide on the pressures at which to operate the column, whether to use upflow or downflow through the column, what flow rates to use, and how long each extraction should last to provide meaningful data.

An individual experiment consists of charging the extrac-

TABLE 1
Discussion Topics

1. Should the column exit stream be saturated with naphthalene?
2. Discuss how you evaluated the mass transfer coefficient, k .
3. For packed beds, the mass transfer coefficient is often represented as a function of the N_{Re} , N_{Sc} , and N_{Gr} numbers, if that function takes the following form, determine the values of the constants a , b , c , and d .

$$\frac{k}{\sqrt{0}} = a(N_{Re})^b (N_{Sc})^c (N_{Gr})^d$$

4. What is the fugacity coefficient of the solute in the condensed phase at its sublimation pressure?
5. Use the Peng-Robinson or other suitable equation of state to predict the solubility of the solute in the supercritical solvent. How well does the equation of state prediction compare to the solubility reported in the literature?
6. How much energy input is required to maintain isothermal conditions across the micro-metering valve?
7. Support your decision to operate the column in either the upflow or downflow configuration.

tion column with a known amount of naphthalene (filling the rest of the column void with sand), re-assembling the system, pressurizing the system to the desired operating pressure at a chosen temperature, and initiating flow of supercritical carbon dioxide. Periodic measurements of feed-pump and column pressure, column and extract-receiver temperature, and instantaneous and cumulative carbon-dioxide flow rates are taken.

Once each individual extraction is completed, the column is re-weighed to obtain the quantity of naphthalene extracted. The column, rather than the naphthalene recovered in the extract receiver, is weighed because it is difficult to account for all the naphthalene in the receiver without the addition of another solvent. Some naphthalene usually precipitates on the piping walls after the micro-metering valve assembly. (This needs to be cleaned out between each experimental run.) Given this, less error is introduced into the experiment by doing the simple loss-in-weight measurement on the column.

Safety is a key aspect of the laboratory for two reasons. First and foremost is to ensure the safety of the students performing the high-pressure experiment; second is the heightened appreciation for safety the students gain from completing a high-pressure experiment such as this. To perform this experiment safely, students are required to develop a level of proactive thinking that they are not typically required to have in other unit operations laboratory experiments (*i.e.*, fluid flow, efflux time of a tank, or pressure drop in a packed column). The students must evaluate all the possible outcomes of their actions prior to doing anything with the equipment to make sure that the desired result is obtained safely. Students are not allowed to operate the equipment until they have demonstrated reasonable safety awareness to the instructor. This is not to say that the previously mentioned experiments should be performed casually or unsafely, but rather that the chance for serious injury is greater when performing a high-pressure experiment such as SCFE. This creates an atmosphere in which the students take lab safety very seriously. Providing this heightened level of safety awareness was a significant underlying objective of the laboratory and was one of the key reasons this experiment (High-Pressure Supercritical Extraction) was considered rather than something such as a simple wetted-wall mass-transfer experiment.

Some of the key safety instructions given to the students are

- *No work can be done on the extraction column or associated piping until the system has been depressurized and then verified. Verification of depressurization is accomplished by opening all valves around the column and making sure that **both** inlet and outlet pressure gauges read zero and that there is no discharge from either of the two vents. Even if the column discharge is plugged, the inlet pressure*

gauge should still read zero when the column is depressurized. If this state is not obtained, the students are required to obtain help from either the instructor or the teaching instructor in the lab.

- *No work should be done on the extraction column while it is plumbed up and in place on the extraction unit. All work should be completed while the column is out of service and on the workbench. Additionally, step-by-step instructions for loading and unloading the extraction column are located in the appendix of the student laboratory.*
- *The maximum operating temperature set in the student laboratory is 55°C. While this was done to make sure that the column operating pressure would not exceed design limits, it also prevents liquid naphthalene from being pushed out of the column because the 55°C limit is significantly lower than the 80-82°C naphthalene melting point.*

Finally, with regard to safety, the students should be made aware of the issue of retrograde condensation within SCF systems. This is the phenomenon that can occur when vapor-liquid equilibrium exists at a temperature or pressure above the mixture critical point. In such a situation, increasing the operating temperature at constant pressure may lead to condensation. This can be a problem in the student experiment where the micro-metering valve and discharge piping are electrically heat traced to prevent freezing. The students should be cautioned to use the heat tracing only to maintain isothermal conditions in this part of the system and not to add unnecessary heat. Should retrograde condensation occur at the inlet of the micro-metering valve, the possibility of the system being plugged increases and the system will need to be depressurized as outlined above in the first bullet. The naphthalene-CO₂ system is susceptible to retrograde condensation when the operating pressures are around 125 bar and below.

Analysis

The first step in the analysis is for the students to ensure that the carbon dioxide exiting the column is not saturated with naphthalene (first discussion topic in Table 1). This could happen if either the naphthalene/sand ratio charged to the column is too large or if the carbon dioxide flow rate is too small. In these cases, the effective contact time may be long enough for saturation to occur. This, of course, would render any mass transfer coefficient calculations meaningless.

Students can then determine the mass transfer coefficient, *k*, from the well-known relationship

$$\frac{C_1 V^0}{Az} = k \Delta C_{LM} \quad (1)$$

where *C*₁ is the average naphthalene concentration in the exit

stream (as determined by material balance), V^0 is the empty-column superficial velocity, A is the surface area per unit volume, z is the naphthalene packed-bed length, and ΔC_{LM} is the log-mean concentration difference across the column defined as

$$\Delta C_{LM} = \frac{(C_1^{\text{sat}} - 0) - (C_1^{\text{sat}} - C_1)}{\ln \frac{C_1^{\text{sat}} - 0}{C_1^{\text{sat}} - C_1}} \quad (2)$$

where C_1^{sat} is the naphthalene concentration at saturation (*i.e.*, the solubility). Thus ΔC_{LM} represents the effective driving force for the extraction. All of these quantities can be determined from measured experimental quantities except for the surface-to-volume ratio A (which is given to the students) and C_1^{sat} , which the students are asked to estimate from an equation of state such as Peng-Robinson (discussion topic #5). The subject of high-pressure phase behavior, including topics such as equilibrium between a solid and a supercritical fluid phase, is covered in the undergraduate thermodynamics sequence at New Jersey Institute of Technology. The pertinent equation is

$$C_1^{\text{sat}} = \frac{M_1}{V} y_1 = \frac{M_1}{V} \frac{P_1^{\text{sat}}}{P} \exp \left[\frac{V_1^{\text{sol}} (P - P_1^{\text{sat}})}{RT} \right] \frac{1}{\hat{\phi}_1} \quad (3)$$

where P_1^{sat} is the vapor pressure of the solid phase at the system temperature, V_1^{sol} is its molar volume, M_1 is its molecular weight, y_1 is its mole fraction in the supercritical fluid mixture at saturation, V is the molar volume of the supercritical fluid mixture, and $\hat{\phi}_1$ is the solute fugacity coefficient in the supercritical fluid mixture. Each of the latter two quantities are determined by the chosen equation of state. The equation must be solved iteratively for y_1 since the fugacity coefficient is a function of composition. Alternatively, the students could obtain a value for C_1^{sat} from the literature for this quantity.

The value of A , the surface-to-volume ratio for the packed bed, has been experimentally estimated using the student equipment and is given to them. This value is only an order-of-magnitude estimate as it will change each time the column is repacked with fresh naphthalene. This is because the naphthalene crystals are not very uniform in size or shape. This estimate could be improved by adding a size reduction/classification step to the naphthalene to make it more uniform in terms of size and shape. This operation would not necessarily be part of the student experiment, but rather an operation a teaching assistant would perform to ensure that the naphthalene was uniform.

During the experiment the students should have evaluated the mass transfer coefficient k at several different sets of operating conditions. This should allow them to correlate k with key operating conditions. A typical correlation for SCF

applications might have a form such as^[7,8]

$$N_{Sh} = f(N_{Re}, N_{Sc}, N_{Gr}) \quad (4)$$

where N_{Sh} is the Sherwood number (kz/D_{AB}), N_{Re} is the Reynolds number ($DV^0\rho/\mu$), N_{Sc} is the Schmidt number ($\mu/D_{AB}\rho$), and N_{Gr} is the Grashof number ($d^3g\rho\Delta\rho/\mu^2$). Here, D_{AB} is the diffusivity, D is the column diameter, ρ is the fluid density, $\Delta\rho$ is the density difference between the saturated interface and the bulk, unsaturated fluid, μ is the fluid viscosity, and d is the average particle diameter. The Grashof number, not generally needed in sub-critical fluid applications, is included to account for buoyancy effects. These arise due to the relatively high density and low viscosity and thus exceptionally low kinematic viscosities of supercritical fluids.

The students are thus expected to evaluate the constants in an expression such as

$$\frac{k}{V^0} = a(N_{Re})^b (N_{Sc})^c (N_{Gr})^d \quad (5)$$

Obtaining sufficient data to evaluate all four constants should be one of the objectives when the students develop their experimental plan. In preparing for the experiment, they are expected to have consulted the provided references^[9,10] for determining quantities such as viscosity and diffusivity.

In their write-up, the students are expected to address each of the discussion topics listed in Table 1. The first three topics relate to the experimental determination of k , as already described. The remaining topics require that the students comprehend various thermodynamic aspects of SCFE. These include fugacities of solids at high pressures, use of equations of state for high-pressure phase equilibrium, and the Joule-Thomson effect.

CLOSING REMARKS

Student response to this experiment has been generally positive. They enjoy the “hands-on” experience associated with assembling and disassembling the apparatus, the exposure to a non-traditional unit operation, and the combination of mass transfer and high-pressure thermodynamics in a practical application.

The principal experimental difficulty has been deposition of naphthalene in the discharge line and in the micro-metering valve. This can be alleviated by ensuring that the exiting stream is well removed from saturation. With proper choice of operating conditions, however, the experiment works well as designed. Students can complete several individual experiments in the allotted time of two five-hour laboratory periods.

An alternative experimental set-up would be to replace the discharge line and condensate receiver with a “U-tube” in a cold trap. While this idea is yet to be attempted experimentally, one can envision weighing the tubing (including the

“U-tube”) downstream of the micro-metering valve before and after each trial as an alternative to obtaining the amount of naphthalene extracted in the experiment. The mass of the extracted naphthalene would be a more significant portion of the total mass of the sample and apparatus being weighed. In this manner, more accurate results may be possible.

If multiple groups complete the lab during the semester, another enhancement to the laboratory experience could be to have the different groups use different solute materials. At the end of the semester, a comparison of the correlation constants from each group could be completed and this could be used to create a generalized correlation. Possible alternative solutes include biphenyl and benzoic acid. Should this approach be taken, it is important to remember that the value of A, the surface-to-volume ratio in Eq. (1), must be provided for each system investigated.

In summary, this laboratory experiment provides a valuable introduction to a modern unit operation in the chemical process industry while at the same time it encourages creative thinking in the synthesis of concepts from disparate areas of chemical engineering.

NOMENCLATURE

- A Surface area per unit volume of a packed bed (m^2/m^3)
 a,b,c,d Correlating equation parameters
 C_1 Average concentration of naphthalene in exiting carbon dioxide (kg/m^3)
 C_1^{sat} Concentration of naphthalene in carbon dioxide at saturation (kg/m^3)
 ΔC_{LM} Log mean concentration driving force (kg/m^3)
 D Column diameter (m)
 D_{AB} Diffusivity (m^2/sec)
 d Particle diameter (m)
 g Acceleration due to gravity (m/sec^2)
 k Mass transfer coefficient (m/sec)
 P Pressure (bar)
 P^{sat} Vapor pressure of solute (bar)
 R Ideal gas constant ($\text{m}^3\text{bar}/\text{molK}$)
 T Temperature (K)
 V Molar volume of fluid phase (m^3/mol)
 V^{sol} Molar volume of solute (m^3/mol)
 V^0 Empty column superficial velocity (m/sec)
 z Packed bed length (m)
 ρ Density (kg/m^3)
 μ Viscosity ($\text{kg}/\text{m sec}$)

Dimensionless Numbers

- N_{Gr} Grashof number ($d^3g\rho\Delta\rho / \mu^2$)
 N_{Re} Reynolds number ($DV^0\rho / \mu$)
 N_{Sc} Schmidt number ($\mu / D_{\text{AB}}\rho$)
 N_{Sh} Sherwood number (kz / D_{AB})

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Multimedia Fluid Mechanics

Continued from page 95.

The CD is neither a book nor a collection of movie clips. It is truly a seamlessly integrated multi-media tool. The user can read some brief text describing the phenomenon, can look at the equations and see the meaning of each term, and also look at some movie clips that will drive the point home. Most importantly, there are a number of very simple, but cleverly designed, interactive experiments where the user can take data off of a running movie clip and process the automatically tabulated data in order to investigate the dimensional relationships and gain valuable insights. These interactive experiments constitute very nice classroom demonstrations to supplement lectures. An equation feature that is used cleverly is a roll-over feature where as the mouse pointer is dragged over each term of the equation, the term is magnified and highlighted, and its meaning pops up in a small text box.

I cannot overemphasize how well this CD is done. The selection of the topics, the level of coverage, and the actual presentation are all superb. There are many hyperlinks throughout the CD; however, unlike some other CDs where the user can hyperlink his/her way into a digital purgatory, on this CD one can always return to the page of interest using the small navigation map at the top of the page.

Congratulations to Professor Homsy and his colleagues for undertaking the much-needed task of creating a new tool for aiding students of fluid mechanics. Also, congratulations for holding the line on the price, which is extremely reasonable in an environment of skyrocketing textbook prices. □

Random Thoughts . . .

FAQS. III GROUPWORK IN DISTANCE LEARNING^[1]

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Of all the instructional methods we advocate in our teaching workshops, the ones we emphasize most involve students working together in small groups. Workshop participants invariably ask whether such collaboration is possible in distance learning. The answer is that it may take some additional effort by the instructor, but it can be done and done effectively.

In this column we offer ideas for getting students at remote sites to collaborate when attending lectures in a synchronous course, working through lessons in an asynchronous course, and doing homework in either distance mode. Other references outline the hows and whys of using groupwork in traditional class settings^[2,3] and discuss the educational value of distance learning compared to traditional classroom instruction.^[4]

In synchronous lectures, brief group exercises can be assigned just as they are in traditional classrooms. (Ask a question or assign a short problem to pairs or small groups of students, stop them after 30 seconds–3 minutes, collect answers, provide the correct answer if necessary, and move on.) The instructor may announce in the first class that such exercises will be interspersed throughout the lectures to provide practice for the homework and tests, adding that the students at the remote sites can either do the exercises as instructed, in which case they will learn how to do them, or just sit there and watch, in which case they'll quickly get bored and learn little or nothing. If some students choose not to participate, the loss is theirs.

A similar procedure may be followed for asynchronous course offerings that go out on videotape or web-based media. When the students come to an exercise in a taped or streamed presentation they can either (a) pause the presentation, try the exercise (ideally with others who may be physically or virtually present with them), and then fast-forward to the point in the presentation where the answer is pre-

sented, or (b) just do the fast-forwarding. The instructor should present both options in the first class and strongly suggest that if the students really want to learn the material they will choose the first one. Students may be helped to connect with one another in small groups to view the classes and work through the exercises via instant messaging, e-mail, threaded discussion, and ftp transfers. In addition, growing numbers of on-line students—especially those in industry—have access to videoconferencing facilities with electronic whiteboards. With those tools, virtual teams can almost (but not quite) duplicate the in-person team experience.

The first step in getting students at remote sites to collaborate on problem sets or projects is to organize virtual teams and set them up to interact electronically using any of the tools mentioned above. Simply asking students to do something in groups is not enough to guarantee effective learning, however, as anyone who has ever tried it knows. Even in traditional classes students may do little or no work but get the same grade as their more industrious colleagues, and serious conflicts may arise between teammates with varying levels of ability and senses of responsibility. The problems may be even worse when groups are virtual and don't have the self-regulating capability provided by face-to-face meetings. It is therefore particularly important in distance classes to adhere to the defining principles of cooperative learning,

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especially positive interdependence (if anyone fails to do his or her part, everyone loses in some way), individual accountability (all team members are held accountable for all the material in the assignment), and regular self-assessment of team functioning.

Standard references offer guidance on how to meet the criteria for cooperative learning in traditional classes,^[3] and tips for making groupwork effective in a distance setting are given by Millis^[5] and Bailey and Luetkehans.^[6] The following suggestions are drawn from these sources.

1. Make it clear to the students why groupwork is being required.^[5] This admonition is particularly important for students in distance courses, whose learning preferences tend to favor working independently.

2. Form small teams that are balanced in knowledge and skills.^[5,6] Teams of three or four are large enough to provide adequate diversity of opinions, experiences, and learning styles, but not so large that individual members can successfully hide. Groups of all strong students or all weak students should be avoided. If possible, at least one member of each team should have experience with the computer tools to be used to complete the assignments.

3. Give clear directions regarding both the assignments and the communication tools.^[5] Virtual groups may find it particularly frustrating to have to decipher muddled directions about what to do and how to do it, and their frustration could hurt both their motivation and their performance. Give short preliminary assignments that require the team members to demonstrate their mastery of the communication software.

4. Monitor team progress and be available to consult when teams are having problems.^[5,6] The tendency of some students in traditional classes to let groupwork slide in the face of other time demands is likely to be worse when the team members never see each other face-to-face. Appoint team coordinators whose responsibilities are to keep their teams on task and to report on progress and problems at regular intervals. Periodically rotate this role among team members. Prompt groups that are not meeting frequently enough and offer guidance if they appear to be stuck.

5. Intervene when necessary to help teams overcome interpersonal problems.^[6] Suggest strategies like active listening to resolve conflicts. (Each side makes its case, and the other side has to repeat that case to the first side's satisfaction without attempting to counter it. When both sides have

had their say, a resolution is sought.) Consider conducting such sessions by videoconference or telephone rather than asynchronously.

6. Collect peer ratings of individual citizenship and use the ratings to adjust the team assignment grades.^[5] Rewarding exceptional team members and penalizing non-contributors helps avoid many of the conflicts and resentments that often occur when students work on group projects. A procedure for collecting ratings and using them to adjust team grades is described in the literature.^[7]

7. Anticipate problems and get help when necessary.^[5] You can be reasonably certain that any problem you encounter in groupwork has already been encountered by others and is addressed somewhere in the literature. When a problem arises, check the references^[2,3] to make sure you have not forgotten any of the elements of good practice in cooperative learning and ask knowledgeable colleagues or faculty development center personnel to help you strategize remedies.

... working together in small groups... in distance learning... may take some additional effort by the instructor, but it can be done and done effectively.

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All of the *Random Thoughts* columns are now available on the World Wide Web at http://www2.ncsu.edu/effective_teaching/ and at <http://che.ufl.edu/~cee/>

THE BUSINESS MEETING

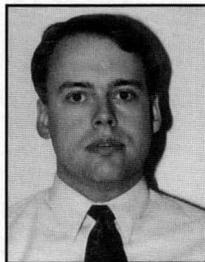
An Alternative to the Classic Design Presentation

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There is an increasing consensus among academics and practicing engineers that effective communication skills should be an integral part of an engineering education.^[1-3] When engineers who have been out of school for ten years are asked “What courses do you wish you had taken?”, Kranzber^[4] reports that the most common answer is “English courses.” Both ABET^[5] and the rest of the technical community^[6] recognize that communications are part of a broader package of interpersonal, communication, and teamwork skills that Seat and Lord^[7] refer to as “performance skills.”

Many educationally focused programs, including the programs at Rowan^[8] and the University of North Dakota,^[9] have integrated technical communication into their core engineering curriculum. In many cases, however, oral communication exercises in engineering consist of little more than giving repeated technical Powerpoint[®] presentations to an audience and answering a few brief questions at the end. Such an exercise emulates a presentation at a technical conference, but resembles very little else in the business world. There is no doubt that this presentation format is valuable, but it should not be the only experience that an undergraduate engineering student receives.



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Conducting a business meeting instead of a final presentation in a senior plant-design course provides an alternative to ANOTHER formal oral presentation. In this model, student teams plan and conduct a formal business meeting with faculty and industrial representatives serving in formalized roles. Details of the process are provided below.

THE PROCESS

Each design team is asked to conduct a business meeting with the Executive Committee of their company/customer. The Executive Committee consists of the

- *Chief Executive Officer*
- *Engineering Director*
- *Finance Director*
- *Marketing/Sales Director*
- *Safety/Environmental Director*
- *Proposed Plant Manager*

Obviously, the number of members on the Executive Committee and their specific roles can be altered to accommodate the number of faculty and/or industrial representatives attending the presentations. Each group makes a formal presentation to this committee, including a description of the proposed process, relevant design issues, an economic analysis, and recommendations. This presentation should not exceed thirty minutes. During the presentation, the committee limits itself to questions of clarification.

Following the formal presentation, the members of the committee will ask questions of the design group. Committee members may address their questions to the team as a whole, or to specific members. Although there is no time limit to the questioning period, 20 to 25 minutes represents a typical length of time. During the presentation, the speaker

stands at the overhead projector or computer while the other group members are seated facing the committee. All group members are seated during the questioning.

TEAM ROLES

Each member of the design group should perform a specific function on the team. At least three distinct roles that must be filled are

The Team Leader • This member is responsible for providing the introductory materials and anything dealing with the “big picture.” Team-leader responsibilities include making sure that all members of the group are given sufficient opportunities to participate in the questioning and that every question receives an adequate answer.

The Economics Expert • This member is responsible for presenting the economic analysis and fielding detailed questions about economic calculations and other issues.

The Engineering Expert • This member is responsible for presenting the technical aspects of the process including equipment selection, sizing, and processing issues. This person should be prepared to justify technical assumptions and other process decisions.

Teams with four members can divide either the economics or engineering issues between two members, but there must be only one team leader. Obviously, these positions may be further divided, or additional roles may be added to accommodate larger teams.

Student learning is disserved if individual members of a design team spend the semester focusing on only a single aspect of the design process. To avoid this dilemma, the faculty member’s selection of the engineering expert and the economics expert should be made and announced to the team only 48 hours before the presentation. Using this approach, team members cannot know which section of material they will be responsible for discussing and are more likely to work on all aspects. The team may pick its own leader.

GRADING

An ongoing concern with group projects is how to effectively account for individual performance in team projects.^[10] In this business meeting, grading can account for both team and individual performances. It is reasonable for students to feel that their grades should not be destroyed by a weak performance from an unmotivated student. At the same time, a weak member can negatively impact the effectiveness of the team presentation. Thus, a division between team and individual points seems appropriate. On the presentation itself, the team as a whole is graded on a five-point scale based on the following items:

- *Visual Aids (Clarity; Font Size; Usefulness)*
- *Organization (Appropriate Structure and Flow?)*
- *Introduction (Grabs Attention? Appropriate Content?)*
- *Body (Completeness; Accuracy; Clarity; etc.) [x3]*
- *Summary (Concise? Covered Key Points?)*
- *Overall Effectiveness (Speaker’s Goals Accomplished?)*

Total Possible Points: 40

Thus, each team member receives the same score from these 40 points. Individual team members are also evaluated on

- *Delivery (Volume; Clarity; Rate; etc.)*
- *Poise and Appearance (Appropriate Dress? Nervousness? etc.)*

Total Possible Points: 10

Thus, every team member can receive up to fifty points from the presentation. Forty of these points are the same for every member, while ten points vary from member to member. This division of team and individual grading makes all members accountable for the success of the team while at the same time it maintains individual distinctions.

The questioning period also results in a portion of the grade, but the mechanism is different for the experts and the team leader. Each expert is evaluated on the following

- *Poise (Calmness, Ability to “Think on One’s Feet”) [x2]*
- *Ability to Answer [x2]*
- *Interaction with Audience (Eye Contact? Demeanor)*

Total Possible Points: 25

Thus, each expert has 25 possible points for his or her role during questioning. The experts’ total for the presentation and questioning is divided by 7.5 to provide a 1-10 grade. The team leader has additional responsibilities during the questioning, so his or her scoring is more involved. It is evaluated on

- *Poise (Calmness, Ability to “Think on One’s Feet”) [x2]*
- *Ability to Answer [x2]*
- *Interaction with Audience*
- *Distribution (All Group Members Used?) [x2]*
- *Responsibility (Questions Suitably Answered?) [x2]*

Total Possible Points: 45

Each team leader has his or her total score divided by 9.5, resulting in the same 1-10 grading as the experts. It is important to note that the team leader does not receive more credit than the other team members, but that more of the team

leader's grade is determined by the questioning. A sample grading sheet is shown in Table 1. Obviously, the categories can be expanded, altered, or weighted differently to accommodate different priorities of design faculty.

SELECTION OF EXPERTS AND TEAM LEADERS

Design teams select their own team leaders, while experts are assigned by the faculty member in charge, with only 48 hours advance notice. The team leader is responsible for sending all members of the Executive Committee a brief e-

mail that includes

- A formal invitation to the meeting, including mention of the time and place
- A statement identifying the team leader and other experts
- A brief summary of the topic to be discussed during the meeting

The e-mail must be sent at least 24 hours before the meeting.

RESULTS

The business-meeting format has proven successful at two different universities. Students reported that they "felt more like a team" and were "less stressed" by the presentation format. Students with internship or other industrial experience reported that the format was more realistic and closer to what they experienced in their jobs. Overall, the students rated the new format a 4.73 out of a possible 5.00 when asked to rate the effectiveness of the business meeting.

The faculty have also enjoyed this method. Because of the group format, there was more time for detailed questioning. It was also easier to evaluate both group and individual performances. Other universities, including the Universidad Nacional de Salta in Argentina, have expressed interest in this idea and it is presently being implemented at the Israel Institute of Technology. Overall, the business meeting provided a useful alternative to a classical oral presentation.

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TABLE 1			
Final Meeting Grade Report			
(NOTE: x2 = double-weighting; x3 = triple weighting)			
Evaluator _____			
Project _____			
Common Presentation Grades:			
• Visual Aids (Clarity; Font Size; Usefulness)	_____		
• Organization (Appropriate Structure and Flow?)	_____		
• Introduction (Grabs Attention?: Appropriate Content?)	_____		
• Body (Completeness; Accuracy; Clarity; etc.) [x3]	_____		
• Summary (Concise? Covered Key Points?)	_____		
• Overall Effectiveness (Goals Accomplished?)	_____		
			Total Points _____
<hr/>			
	<u>Team Leader</u>	<u>Economics</u>	<u>Technical</u>
Delivery	_____	_____	_____
Poise and Appearance	_____	_____	_____
(Questioning)			
Poise [x2]	_____	_____	_____
Ability to Answer [x2]	_____	_____	_____
Audience Interaction	_____	_____	_____
Distribution [x2]	_____	_____	_____
Responsibility [x2]	_____	_____	_____
Individual Totals			
<hr/>			
	<u>Group Leader</u>	<u>Economics</u>	<u>Technical</u>
Team Total	_____	_____	_____
Individual Total	_____	_____	_____
Grand Total	_____	_____	_____
<hr/>			
Score	_____	_____	_____

Editorial Note: The "Class and Home Problems" section on pages 366-368 of the Fall 2000 issue of CEE presented Erich A. Muller's article, "A Thermodynamics Problem with Two Conflicting Solutions." In it, tanks A (isothermal) and B (adiabatic) are filled with an ideal gas and connected by pipes and a valve. Initially, $p_A > p_B$. If the valve is opened and equilibrium attained, will it have been necessary to add (or remove) heat from tank A? Professor Muller's article has elicited the following two letters. His reply is also appended.

We appreciate the interest that Professor Muller's problem has generated, and request that any further correspondence on this problem be e-mailed to him at

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To the Editor:

The recent article by Müller^[1] presents an interesting discussion of pedagogically important issues. We wish to comment on two aspects of the article. First, we believe that it is pedagogically more sound to treat Müller's "two conflicting solutions" as (non-conflicting) solutions to different problems that arise from two different equilibrium *models* of the situation, as implied in his comments. Second, we believe that his "Comments on the Equation for the Uniform State, Uniform Flow Model" can be improved regarding the basic assumptions underlying use of the unsteady-state energy-balance equation for a control volume and its general application in first-law analysis. We elaborate on both these points in the following.

Concerning the analysis of the situation described in the article, we note that his "Solution #1" relates to a model in which it is stated that "tank B is adiabatic"; that is, there is no heat transfer to or from tank B ($\dot{Q} = 0$) at any time to any other body, although this does not preclude exchange of energy via flow of matter through the connecting line and valve. Practically speaking, the equilibrium state for the contents of tank B is a partial equilibrium state with respect to the contents of tank A: mechanical, but not thermal, equilibrium. Regardless of where the control surface is placed (around tank A alone or around tanks A and B together), the conclusion reached is as Müller states: $Q^A > 0$. Solution #1 is the solution to the problem arising from one particular model of the situation.

His "Solution #2" relates to a different model of the situation, in which it is stated that there is "a heat transfer between the tanks" (presumably through the connecting line and valve). In this case, tank B evidently has an adiabatic enclosure with a (small?) diathermal hole in it. This changes the equilibrium aspect of the model to be addressed, to one allowing for both mechanical and thermal equilibrium with

respect to the contents of both tanks. This also changes the conclusion reached for the resulting problem to, as Müller also states, $Q^A = 0$.

We thus believe that it is pedagogically better to treat the two cases as two different models of the situation and to compare the results of a first-law analysis of the resulting problems, rather than to present the results as two conflicting solutions of the same problem. Müller cannot on the one hand state that "tank B is adiabatic" and on the other state that there is "a heat transfer between the tanks." Thermodynamics requires *precise*, rather than "shrewd," statements of models and systematic analysis of resulting problems.

Concerning his "Comments on the Equation for the Uniform State, Uniform Flow Model," we feel that Müller's justification of his starting point for solution #1, as a consequence of a general first-law analysis for a control volume, can be strengthened. This strengthening is pedagogically important, to enable students to appreciate points at which approximations are made to exact equations.

His "generalized energy balance," Eq. (7), should be replaced by (we also change the sign of \dot{W} , in accordance with recommended practice)

$$\frac{d}{dt} \left[m_{\text{sys}} (\tilde{u}_{\text{sys}} + \tilde{e}_{k,\text{sys}} + \tilde{e}_{p,\text{sys}}) \right] = \dot{Q} + \dot{W} + \sum_{\text{inlets}} \dot{m}(t) [\tilde{h}(t) + \tilde{e}_k(t) + \tilde{e}_p(t)] - \sum_{\text{exits}} \dot{m}(t) [\tilde{h}(t) + \tilde{e}_k(t) + \tilde{e}_p(t)] \quad (\text{A})$$

In Eq. (A), u , e_k , e_p , and h denote specific internal energy, kinetic energy, potential energy, and enthalpy, respectively, and a tilde ($\tilde{}$) denotes an appropriately defined intensive

quantity. Thus, for a property within the control volume (sys)

$$\tilde{u}_{\text{sys}}(t) = \frac{U_{\text{sys}}(t)}{m_{\text{sys}}(t)} = \frac{\int_V u(\mathbf{z},t)\rho(\mathbf{z},t)dV}{\int_V \rho(\mathbf{z},t)dV} \quad (\text{B})$$

and similarly for $\tilde{e}_{k,\text{sys}}$ and $\tilde{e}_{p,\text{sys}}$. In Eq. (B), dV is a volume element, ρ is density, and \mathbf{z} denotes a point within the control volume. Correspondingly, for a property at an inlet or exit

$$\tilde{h}(t) = \frac{\dot{H}(t)}{\dot{m}(t)} = \frac{\int_A h(\mathbf{x},t)\rho(\mathbf{x},t)u_n(\mathbf{x},t)dA}{\int_A \rho(\mathbf{x},t)u_n(\mathbf{x},t)dA} \quad (\text{C})$$

and similarly for $\tilde{e}_k(t)$ and $\tilde{e}_p(t)$. In Eq. (C), dA is an area element of an inlet or exit area, \mathbf{x} denotes a point on the area, and u_n is the flow velocity normal to dA . Eqs. (A) to (C) must be supplemented with the mass-conservation equation

$$\frac{dm_{\text{sys}}}{dt} = \sum_{\text{inlets}} \dot{m}(t) - \sum_{\text{exits}} \dot{m}(t) \quad (\text{D})$$

The validity of Eq. (A) rests on two generally accepted concepts not introduced by Müller: the *continuum hypothesis* and a *local equilibrium hypothesis*. The former allows integration of point properties over volumes and areas, as in Eqs. (B) and (C), and the latter allows calculations using macroscopically based property relationships.

Equations (A) and (D) are differential equations. As in some introductory texts,^[2,3] it is tempting to deal instead with their integrated forms, between times t_1 and t_2 , say,

$$\begin{aligned} m_2(\tilde{u}_2 + \tilde{e}_{k,2} + \tilde{e}_{p,2}) - m_1(\tilde{u}_1 + \tilde{e}_{k,1} + \tilde{e}_{p,1}) \\ = Q_{12} + W_{12} + \sum_{\text{inlets}} \int_{t_1}^{t_2} \dot{m}(t) [\tilde{h}(t) + \tilde{e}_k(t) + \tilde{e}_p(t)] dt - \\ - \sum_{\text{exits}} \int_{t_1}^{t_2} \dot{m}(t) [\tilde{h}(t) + \tilde{e}_k(t) + \tilde{e}_p(t)] dt \quad (\text{E}) \end{aligned}$$

$$m_2 - m_1 = \sum_{\text{inlets}} m_i - \sum_{\text{exits}} m_e \quad (\text{F})$$

Equations {(A),(D)} and {(E),(F)} are exact. Equation (E) is only a *formal* result and may not always be useful, however. This form is deceiving since it implies neglect of any interdependence of the left and right sides of Eq. (A).

Simplification of Eqs. {(A),(D)} or {(E),(F)} involves invoking appropriate approximations for special cases of the spatial and temporal dependence of the properties at the inlets and exits and of the system. Important special cases are

- *uniform flow*, for which the properties *at an inlet or exit* are independent of position \mathbf{x} (giving $\tilde{h}(t) \equiv h(t)$) (or for each phase of the flow)
- *uniform state*, for which the properties *of the system* are independent of position \mathbf{z} (giving $\tilde{u}_{\text{sys}}(t) \equiv u_{\text{sys}}(t)$) (or for each phase within the system)
- *steady-property flow*, for which the properties *at an inlet or exit* are independent of time t
- *steady flow*, for which \dot{m} *at an inlet or exit* is independent of time t (steady flow usually implies steady-property flow, but the converse is not necessarily true)
- *steady state*, for which the properties *of the system* are independent of time t ; this entails the vanishing of the left side of Eq. (A) (steady state usually implies steady flow and steady-property flow)

The uniform flow (UF) assumption at inlets and exits (incorporated without comment by Müller in his Eq. 7) and the uniform state (US) assumption for the system are often used in the absence of any information concerning spatial dependence of the properties. (The former is consistent with a plug-flow assumption and the latter with a well-stirred vessel assumption.) Together, they form part of the basis for an unsteady-state flow model referred to by Müller as the "Uniform-State Uniform-Flow (USUF) model." This designation by itself is misleading, however, since this model includes a third assumption that corresponds to the steady-property flow assumption defined above. As essentially pointed out by Müller, these three assumptions (together with neglect of kinetic and potential energy terms) allow Eq. (E) to be simplified to Müller's Eq. (1), his "working equation" of the USUF model.

More generally, for unsteady-state flow processes, the steady-property flow assumption does not hold, and the USUF model is invalid. We do not believe that it should be emphasized pedagogically since it severely restricts the first-law analysis to rather special cases, such as the discharge situation described by Müller in his solution #1 and filling a vessel from a constant-property source/reservoir. We recommend instead that a first-law analysis deal directly with the differential equations (A) and (D) as such. This approach handles all situations (including the USUF model as a special case), and is consistent with the approach of some introductory texts^[4,5] and recent pedagogical articles.^[6,7]

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To The Editor:

In the Fall 2000 Class and Home Problems Column, E.A. Müller^[1] proposes a thermodynamics problem designed to demonstrate that two seemingly correct but incompatible solutions can be found from the thermodynamic analysis of a particular process, and furthermore that such incompatible solutions provide an opportunity to improve one's understanding of thermodynamic analysis.

Müller proposes the following: Consider two tanks, A and B, connected with a valve and initially filled with (ideal) gas at the same temperature, but the pressure in A is greater than the pressure in B. Tank B is well insulated (adiabatic), but tank A is maintained at constant temperature by thermal contact with a heat source or sink.

Müller asks: "If the valve that connects both tanks is opened and equilibrium is attained, will it have been necessary to add (or to remove) heat from tank A?" (Denoted as Q^A .)

For this problem, it is clear that tanks A and B will be at the same pressure at the end of the process. But Müller clearly intends that tanks A and B are also at the same temperature when equilibrium is attained. For tanks A and B to reach the same temperature at equilibrium would require that tanks A and B be in thermal contact. Clearly, the contradiction is that tank B cannot be well insulated (adiabatic) and in thermal contact with tank A. This contradiction appears in both solutions presented in the paper.

Solution #1 is obtained by considering an energy balance on a control volume around tank A and shows that $Q^A > 0$. Müller subsequently argues that this solution is incorrect by considering an energy balance on a control volume around tank B; for this system, the paper (correctly) shows that energy must be removed from tank B if the temperature of tank B is unchanged. Since Müller is treating the temperature of tank B to be the same as tank A (and the temperature of tank A is unchanged), energy must be removed from tank B, which violates the requirement that tank B be adiabatic.

In fact, since tank B is well insulated, the energy balance on tank B in the paper correctly shows that the temperature in tank B will increase at equilibrium.

Solution #2 is obtained by considering an energy balance on a control volume around both tanks and the connecting piping, so that the change in internal energy must equal the heat transfer to tank A (Q^A). Since Müller intends the temperatures in the two tanks to be equal at equilibrium, the internal energy is unchanged, and $Q^A = 0$. As discussed earlier, the temperature in tank B actually increases during the process, so the internal energy of the system increases, and $A^A > 0$.

Another way to show $Q^A \neq 0$ is to consider a system such as the contents of tank A after equilibrium is attained. Now, suppose $Q^A = 0$. The contents of such a system could then be considered to undergo an adiabatic reversible expansion (since $Q^A = 0$). Note however that $(\partial T/\partial P)_S > 0$ for all gases (real and ideal). Therefore, when the pressure in tank A decreases, the temperature in tank A also decreases—but this is a contradiction since tank A must be maintained at a constant temperature. Therefore, Q^A cannot equal 0.

Irrespective of the difficulties expressed above, Müller's point is well made that one's understanding is improved by resolving the dispute between seemingly incompatible thermodynamic analyses.

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Author's Response to Letters to the Editor

I have received many comments, personally and publicly, on the problem I presented in the Fall 2000 issue of *CEE*. As with Levenspiel's original thermo problem, each and every comment is different, ranging from "You chose the wrong answer" to "Send me another one of these problems."

The main message of the paper is that if you use equations straight out of a book and apply them to a problem without fully understanding the assumptions behind the equations, you have a chance of coming to a false conclusion. Nevertheless, I think some readers "missed the point," and I believe further discussion is in order.

The initial problem is clearly stated, especially with regard to the final state: "equilibrium is attained." In a simple system such as this, thermodynamic equilibrium requires the

simultaneous achievement of three conditions: homogeneity of pressures (mechanical equilibrium), homogeneity of temperature (thermal equilibrium), and homogeneity in chemical potential (diffusive equilibrium); i.e., *only* if all three conditions ($P^A = P^B$, $T^A = T^B$, and $\mu^A = \mu^B$) are simultaneously met can we affirm that the system will not change in time if left alone.

Solution #1, as Missen and Smith note, pertains to the achievement of mechanical equilibria, but as is also noted in the original article, leaves a temperature gradient among tanks A and B. Given enough time, mass diffusion must take place, transferring *energy* from tank B to tank A. So, even though tank B has adiabatic walls and thus no heat transfer to the surroundings, it does transfer energy due to a temperature difference.

In hindsight, the phrase "Given enough time, this temperature gradient will produce a transfer between the tanks" should read, "Given enough time, this temperature gradient will produce a mass transfer and consequent energy transfer between the tanks" in order to be unambiguous.

It is clear, however, that there are not two solutions to the problem, even if the catchy title implies so. Only one solu-

tion is possible. Any argument attempting to set solution #1 as the correct one must first disprove solution #2—an impossible task.

Many students and teachers (and Spicer's note is a clear example) apply the textbook equations directly to a problem without further thought on the problem. It is in this sense that I totally agree with the second point noted by Missen and Smith. I believe that one should teach the general energy balance, and for each particular case simplify it accordingly.

The point of the original class problem is that if one starts directly with Eq. (2), one may elude some of the assumptions behind its derivation. One should always start with a generalized equation such as Eq. (7)* and integrate it according to the given problem. Categorizing systems as steady state, uniform flow, etc., and stating formal equations in each case only entices the student to learn a myriad of equations, making things more difficult and prone to errors.

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* Equation (7) is identical (with the exception of the arbitrary sign given to the work) to Eq. (A) of Missen and Smith, not to Eq. (E) as stated in their comment.

ChE book review

Advanced Transport Phenomena

by John C. Slattery

Published by Cambridge University Press, The Edinburgh Building, Cambridge, UK; 734 pages; available in paperback and hardcover

Reviewed by

David C. Venerus

Illinois Institute of Technology

Advanced Transport Phenomena is a new textbook written by Professor J.C. Slattery that represents a revision of an earlier text by the same author: *Momentum, Energy and Mass Transfer in Continua* (1981). Transport phenomena is a fascinating and interdisciplinary subject that is covered by at least one required course in all graduate chemical engineering programs and remains an active area of research. Like its predecessor, the new book is intended for graduate students in engineering.

The text is organized into three topics according to the main subjects of transport phenomena: momentum, energy, and mass transfer. In addition, there are two shorter topics that are covered; kinematics (coming before the three main topics) and tensor analysis (an appendix). Each of the three main topics is divided into three sub-topics that can roughly

be described as the formulation, application, and reduction of transport balance equations. This matrix style of organization, where the columns are the main topics (momentum, heat, and mass) of transport phenomena and the rows provide the components and applications for each topic, is similar to that used in the classic text *Transport Phenomena* by Bird, Stewart, and Lightfoot (BSL), and allows the instructor/reader the flexibility to cover the topics by column or by row.

The style and teaching philosophy of the author are revealed in Chapter 1 (kinematics) where concepts such as motion, velocity, and phase interfaces are introduced. Various transport theorems are developed and used to derive the differential mass balance, or continuity equation, and the jump mass balance from the mass conservation postulate. Hence, the approach taken here and throughout the book is to start from general postulates about the physical world and to convert these postulates into useful conservation equations using formal mathematical tools.

The sub-topic structure is itself instructional in that the reader is forced to recognize the similarities (and differences) between momentum, heat, and mass transfer. In Chapters 2, 5, and 8 (Foundations for...), differential forms of the conservation equations and their corresponding two-dimensional forms (jump balances) are derived simultaneously.

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This is followed by rather lengthy developments on the behavior of materials where the most widely used (classical) constitutive equations are eventually presented. In Chapters 3, 6, and 9 (Differential Balances in...), various transport problems are formulated using the conservation and constitutive equations derived in preceding chapters. These problems, which range in complexity from one-dimensional, steady-state problems to two-dimensional problems that include boundary-layer theory, are solved using both analytical and numerical techniques. Chapters 4, 7, and 10 (Integral Averaging in...) are devoted to deriving reduced forms of the differential balance equations: time-averaged (turbulent flows), area-averaged, local volume-averaged (pseudo continuous media), and global volume-averaged (macroscopic balances).

Appendix A provides a comprehensive review of tensor analysis and includes operations in both rectangular Cartesian and curvilinear coordinate systems.

Scattered throughout each chapter are several worked examples, and each chapter ends with a series of exercises (for which a solution manual is available). At the end of each "Foundations of..." chapter, there is a summary subsection where the reader will find tables with the conservation equations expressed in rectangular Cartesian, cylindrical, and spherical coordinate systems.

There is no question that *Advanced Transport Phenomena* is a comprehensive and carefully prepared textbook. The use of material volumes and transport theorems (rather than stationary differential volumes, as is BSL) to derive differential conservation equations is appropriate for graduate-level courses. Significant attention is given to the behavior of materials and to the entropy inequality and its use in the formulation of constitutive equations.

Another positive aspect of this book is the utilization of jump balances to derive boundary conditions. Jump balances are rarely covered in modern texts on transport phenomena, but are invaluable in situations involving free and/or moving boundary problems. I particularly like the tables in Chapter 2 where the jump mass and jump linear momentum balances are given for several special surfaces in the three main coordinate systems.

Where the optimal balance is between being mathematically rigorous and comprehensive while also developing

physical insight on transport problems is, of course, a matter of preference. Many readers of this book might find that there is too much emphasis on the first two at the expense of the third. As I read through certain portions of the book, I sometimes found myself leafing through page after page of derivation to find the punch line. (From my own rough estimate, there are on average a little more than seven equations per page, or, in the 700-page book, a total of about 5000 equations!) For example, in section 5.3, roughly ten pages are used to transform some general postulates about the thermal behavior of materials into useful results (*i.e.*, viscosity and thermal conductivity are positive, Fourier's law, internal energy can be expressed in terms of density, pressure, temperature, and a heat capacity). Unfortunately, discussion about the physical implications for the different constitutive assumptions used in the development is scant.

Another comment is that the book is almost comprehensive to a fault. For example, readers may find the results from the integral averaging chapters of marginal value, either because the subject is too complex to be developed at an advanced level (*e.g.*, turbulence and pseudo continuous media), or because it was too simple and therefore inappropriate for a graduate-level text (*e.g.*, macroscopic balances). Also, it is unlikely that one will find a situation that calls for the macroscopic moment-of-momentum balance or the jump entropy inequality. These portions of the book could have been better used to provide more physical insight or to analyze moving boundary problems, which are so prevalent in materials science and engineering. Having said that, educators and researchers in this field will be glad to have a single book where the equations needed to handle such a wide variety of transport problems can be found.

Advanced Transport Phenomena is a comprehensive textbook that provides systematic coverage of a challenging subject. It can be used as a primary text for a first-year graduate course on transport phenomena; students with prior exposure to the subject at the level provided by BSL will have a sufficient background. It could also serve as a solid reference book for more advanced graduate courses on fluid mechanics or on heat and mass transfer. My overall impression of the book is positive; I recommend it to those with an interest in teaching graduate-level transport phenomena or to those interested in learning advanced topics in this important and fascinating field. □

The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and that elucidate difficult concepts. Manuscripts should not exceed ten double-spaced pages if possible and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

THERMODYNAMIC PROPERTIES INVOLVING DERIVATIVES

Using the Peng-Robinson Equation of State

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Equations of state are among the marvels of chemical engineering. Though simple and convenient, they may be used to model both liquid and vapor behavior for non-polar and low-polar mixtures.^[1,2] Consequently, such methods are the preferred tools of the hydrocarbon processing industry. It is not often, especially in thermodynamics, that you can do so much with so little. In this article, we calculate thermodynamic properties that contain derivatives, a topic not normally found in textbooks.

There are two motivations for presenting this material. First, the calculations are simple, requiring no iteration or trial-and-error solutions. They are, however, useful items to add to the engineer's toolkit, and they require only critical property and ideal-gas heat-capacity data. Second, it enables the student to use some seemingly abstract equations of thermodynamics to directly make numerical calculations. It is rewarding to see these relationships used to make actual calculations and to observe relative magnitudes of various quantities.

To illustrate the methods, we use the Peng-Robinson equation of state applied to a binary vapor hydrocarbon mixture. There is an almost endless number of derivatives that can be calculated—we will consider only a few of the more commonly encountered ones. It is trivial to simplify the ensuing equations for the special case of a pure component or to apply the equations to any number of components. The equations are valid for both liquid and vapor phases.

PROBLEM STATEMENT

Using the Peng-Robinson equation of state, calculate the

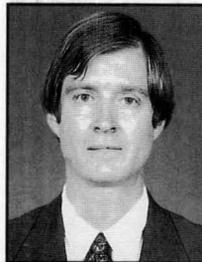
1) Joule-Thompson coefficient, $J \equiv \left(\frac{\partial T}{\partial P} \right)_H$

2) Fluid sonic velocity, $c \equiv \sqrt{\left(\frac{\partial P}{\partial \rho} \right)_S}$

for a binary vapor mixture of n-butane and n-pentane at 390K and 11 bar that consists of 35.630 mole % n-butane. Take k_{ij} for this binary pair to be zero.

SOLUTION

We will solve this problem in three steps. First, we will use the Peng-Robinson equation of state to evaluate the three derivatives involving P , v , and T , *i.e.*, $(\partial P / \partial v)_T$, $(\partial T / \partial P)_v$,



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and $(\partial v / \partial T)_P$. Then we will find the real fluid heat capacities, C_v and C_p , and finally we will apply these results to calculate the two thermodynamic derivatives indicated above.

Solution of the Peng-Robinson Equation of State for

$(\partial P / \partial v)_T$, $(\partial T / \partial P)_v$, and $(\partial v / \partial T)_P$

The Peng-Robinson equation is written as

$$P = \frac{RT}{v-b} - \frac{a}{v(v+b)+b(v-b)} \quad (1)$$

where

R universal gas constant

T absolute temperature

v molar volume

a $a_c \left[1 + m \left[1 - \sqrt{T/T_c} \right] \right]$

a_c $0.45723553 R^2 T_c^2 / P_c$

m $0.37464 + 1.54226 \omega - 0.26992 \omega^2$

b $0.077796074 R T_c / P_c$

T_c critical temperature

P_c critical pressure

ω pitzer acentric factor

The critical properties for the two components of our system are taken from Smith and Van Ness (Table 1).^[3]

For convenience, the Peng-Robinson equation is often written in a cubic polynomial form for the compressibility factor $Z = Pv / RT$

$$f(Z) = Z^3 + \alpha Z^2 + \beta Z + \gamma = 0 \quad (2)$$

where

$$\alpha \equiv B - 1$$

$$\beta \equiv A - 2B - 3B^2$$

$$\gamma \equiv B^3 + B^2 - AB$$

and

$$A \equiv aP / (RT)^2$$

$$B \equiv bP / RT$$

For an N-component fluid with composition, $\{w_i\}$, we calculate the mixture parameters, a and b, from the empirical relations:

$$a = \sum_{i=1}^N \sum_{j=1}^N w_i w_j \sqrt{a_i a_j} (1 - k_{ij}) \quad \text{and} \quad b = \sum_{i=1}^N w_i b_i \quad (3)$$

The binary interaction coefficient, k_{ij} , is exactly zero for $i=j$; for $i \neq j$, k_{ij} is close to zero for hydrocarbons. Values of k_{ij} for many component pairs are available in the literature,^[4] although for most hydrocarbon pairs it is safe to take $k_{ij}=0$. We will henceforth use values without subscripts to refer to

quantities applied to the mixture as a whole, and subscripted values for pure component quantities. From Eq. (1), we calculate the pure component parameters using $R=83.14 \text{ cm}^3\text{-bar/mol-K}$:

$$\begin{aligned} a_1 &= 15911115 \text{ cm}^6\text{-bar/mol}^2 & a_2 &= 23522595 \text{ cm}^6\text{-bar/mol}^2 \\ b_1 &= 72.43235 \text{ cm}^3/\text{mol} & b_2 &= 90.14847 \text{ cm}^3/\text{mol} \end{aligned}$$

and then, from Eq. (3), we find that

$$a = 20631852 \text{ cm}^6\text{-bar/mol}^2 \quad b = 83.836216 \text{ cm}^3/\text{mol}$$

We now solve Eq. (2) for the compressibility factor, Z. This equation is easily solved using Newton-Raphson iteration^[5] or by using the cubic formula.^[1] In either case we calculate the vapor phase compressibility factor (largest of the three real roots) to be 0.7794 for the vapor. Consequently, the molar volume, v, of the vapor mixture is $ZRT/P = 2297.54 \text{ cm}^3/\text{mol}$.

With knowledge of the molar volume and compressibility, we now calculate the three PVT derivatives, which follow directly from the equation of state. Knowledge of these quantities is prerequisite to finding most any derivative thermodynamic property. We know that these three derivatives must satisfy the "cyclical rule," which may be written as

$$\left(\frac{\partial P}{\partial v} \right)_T \left(\frac{\partial T}{\partial P} \right)_v \left(\frac{\partial v}{\partial T} \right)_P = -1 \quad (4)$$

Therefore, once we have values for any two of the three PVT derivatives, the third may be calculated from Eq. (4). We will evaluate each derivative independently, however, and use Eq. (4) to check our work.

The first derivative in Eq. (4) is found by direct differentiation of Eq. (1),

$$\left(\frac{\partial P}{\partial v} \right)_T = \frac{-RT}{(v-b)^2} + \frac{2a(v+b)}{[v(v+b)+b(v-b)]^2} \quad (5)$$

Substituting in the values determined above, we find that

$$\left(\frac{\partial P}{\partial v} \right)_T = -0.0035459 \text{ bar} / (\text{cm}^3 / \text{mol})$$

The second derivative in Eq. (4) is also found by direct differentiation of Eq. (1),

$$\left(\frac{\partial P}{\partial T} \right)_v = \frac{R}{v-b} - \frac{a'}{v(v+b)+b(v-b)} \quad (6)$$

and is found to be 0.0434866 bar/K. Therefore,

$$\left(\frac{\partial T}{\partial P} \right)_v = 22.99558 \text{ K} / \text{bar}$$

The third derivative in Eq. (4) is a bit trickier since Eq. (1) is not readily explicit in volume or temperature. It is therefore found implicitly, using Eq. (2),

$$\left(\frac{\partial v}{\partial T} \right)_P = \frac{R}{P} \left[T \left(\frac{\partial Z}{\partial T} \right)_P + Z \right] \quad (7)$$

where

$$\left(\frac{\partial Z}{\partial T}\right)_P = \frac{\left(\frac{\partial A}{\partial T}\right)_P (B-Z) + \left(\frac{\partial B}{\partial T}\right)_P (6BZ + 2Z - 3B^2 - 2B + A - Z^2)}{3Z^2 + 2(B-1)Z + (A - 2B - 3B^2)}$$

and

$$\left(\frac{\partial A}{\partial T}\right)_P = \frac{P}{R^2 T^2} \left(a' - \frac{2a}{T}\right) \quad \left(\frac{\partial B}{\partial T}\right)_P = \frac{-bP}{RT^2}$$

The derivative term, $a' = da/dT$, may be evaluated directly from Eq. (3) as

$$a' = \frac{da}{dT} = \frac{1}{2} \sum_{i=1}^N \sum_{j=1}^N w_i w_j (1 - k_{ij}) \left(\sqrt{\frac{a_j}{a_i}} a_i' + \sqrt{\frac{a_i}{a_j}} a_j' \right) \quad (8)$$

where

$$a_i' \equiv \frac{da_i}{dT} = \frac{-m_i a_i}{\left[1 + m_i \left(1 - \sqrt{T/T_{c_i}}\right)\right] \sqrt{TT_{c_i}}} \quad (9)$$

The pure component parameters are found from Eq. (9) as

$$a_1' = -25547.0 \text{ cm}^6\text{-bar/mol}^2\text{-K}$$

$$a_2' = -38460.2 \text{ cm}^6\text{-bar/mol}^2\text{-K}$$

and da/dT for the mixture is found from Eq. (8) to be

$$a' = -33543.8 \text{ cm}^6\text{-bar/mol}^2\text{-K}$$

Substituting known values in to Eq. (7), we find that

$$\left(\frac{\partial v}{\partial T}\right)_P = 12.26396 \text{ cm}^3 / \text{mol} - \text{K}$$

If we multiply the three numbers together we will see that we have satisfied Eq. (4).

Calculation of the Heat Capacities

C_v and C_p

We first find C_v . We will consider this real fluid property to be a sum of an ideal gas contribution and a residual correction for non-ideal behavior:

$$C_v = C_v^{ID} + C_v^R \quad (10)$$

The ideal-gas contribution is found using heat-capacity data applicable to gases at very low pressures, which are available in many thermodynamics textbooks. We will use the simple correlation in Smith and Van Ness^[3]

$$C_v^{ID} = R(A + BT + CT^2 + DT^{-2} - 1) \quad (11)$$

which is not recommended for temperatures below 298K nor valid for temperatures over 1500K. For n-butane and n-pentane, the coefficients are given in Table 2.

TABLE 2		
	n-butane	n-pentane
A	1.935	2.464
B	36.915×10^{-3}	45.351×10^{-3}
C	-11.402×10^{-6}	-14.111×10^{-6}
D	0	0

The ideal gas contribu-

tion for the mixture is a mole fraction weighted average of the pure component values, *i.e.*,

$$C_v^{ID} = \sum_{i=1}^N w_i C_{v_i}^{ID} \quad (12)$$

Inserting the known temperature of 390K into the above equations, we calculate for each component

$$C_{v_1}^{ID} = 113.050 \text{ J/mol-K} \quad C_{v_2}^{ID} = 141.376 \text{ J/mol-K}$$

and for the mixture

$$C_v^{ID} = 131.283 \text{ J/mol-K}$$

To calculate the residual contribution to Eq. (10), we use the standard equation found in many textbooks^[4,6] for the residual internal energy derived from the Peng-Robinson equation of state

$$U^R = \frac{Ta' - a}{b\sqrt{8}} \ln \left[\frac{Z + B(1 + \sqrt{2})}{Z + B(1 - \sqrt{2})} \right] \quad (13)$$

The value of C_v^R is calculated from its definition

$$C_v^R \equiv \left(\frac{\partial U^R}{\partial T} \right)_v$$

Evaluation of the partial derivative of Eq. (13) with respect to temperature yields

$$C_v^R \equiv \frac{Ta''}{b\sqrt{8}} \ln \left(\frac{Z + B(1 + \sqrt{2})}{Z + B(1 - \sqrt{2})} \right) \quad (14)$$

with the temperature derivative of Eq. (8) yielding

$$a'' = \frac{d^2 a}{dT^2} = \frac{1}{2} \sum_{i=1}^N \sum_{j=1}^N w_i w_j (1 - k_{ij}) \left[\frac{a_i' a_j'}{\sqrt{a_i a_j}} + \frac{a_i'' \sqrt{a_j}}{\sqrt{a_i}} + \frac{a_j'' \sqrt{a_i}}{\sqrt{a_j}} - \frac{1}{2} \left(\frac{a_i'^2 \sqrt{a_j}}{\sqrt{a_i^3}} + \frac{a_j'^2 \sqrt{a_i}}{\sqrt{a_j^3}} \right) \right] \quad (15)$$

where

$$a_i'' \equiv \frac{d^2 a_i}{dT^2} = \frac{da_i'}{dT} = \frac{a_{c_i} m_i \sqrt{\frac{T_{c_i}}{T}} (1 + m_i)}{2 T T_{c_i}} \quad (16)$$

These equations appear complicated, but the calculation is straightforward, albeit tedious. Pure component parameters for a'' are found from Eq. (16) to be

$$a_1'' = 53.2619 \text{ cm}^6 - \text{bar} / \text{mol}^2 - \text{K}^2$$

$$a_2'' = 80.7496 \text{ cm}^6 - \text{bar} / \text{mol}^2 - \text{K}^2$$

and a'' for the mixture is found from Eq. (15) to be

$$a'' = 70.2732 \text{ cm}^6 - \text{bar} / \text{mol}^2 - \text{K}^2$$

If doing hand calculations, very little error (usually less than 2%) is introduced by using the mole fraction weighted average in calculating a'' . In this case, we would calculate a'' to be $70.9557 \text{ cm}^6\text{-bar/mol}^2\text{-K}^2$. Substituting the above mixture quantities into Eq. (14) (using $Z_L=0.779438$) gives $C_V^R=1.152 \text{ J/mol-K}$.

Using Eq. (10), we now obtain $C_V=132.436 \text{ J/mol-K}$.

We will use an equation analogous to Eq. (10) to calculate C_P ,

$$C_P = C_P^{\text{ID}} + C_P^R \quad (17)$$

and since $C_P^{\text{ID}} = C_V^{\text{ID}} + R$, we readily calculate C_P^{ID} to be 139.597 J/mol-K . The residual contribution may be calculated from the general relationship between C_V and C_P ,

$$C_P^R = C_V^R + T \left(\frac{\partial P}{\partial T} \right)_V \left(\frac{\partial v}{\partial T} \right)_P - R \quad (18)$$

The two partial derivatives are already calculated above and can be substituted into Eq. (18); we find that $C_P^R = C_V^R + 124.85 \text{ cm}^3\text{-bar/mol-K}$ and therefore $C_P^R = 136.37 \text{ cm}^3\text{-bar/mol-K}$, or 13.637 J/mol-K . Adding the ideal gas and residual contributions according to Eq. (17) yields

$$C_P = 153.235 \text{ J/mol-K}$$

Calculation of Thermodynamic Properties J and c

Now that we have values for the three PvT derivatives as well as the two heat capacities, C_V and C_P , we can calculate a large number of thermodynamic derivatives. We will only evaluate two of the more commonly encountered ones, the Joule-Thompson coefficient, J , and the speed of sound in a fluid, c .

It is simple to calculate the Joule-Thompson coefficient, $(\partial T / \partial P)_H$, using the working equation^[6]

$$J = \frac{1}{C_P} \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right] \quad (19)$$

since all the required values have been calculated. Substituting into Eq. (19), we obtain

$$J = 1.62195 \text{ K/bar}$$

The fluid sonic velocity $\sqrt{(\partial P / \partial \rho)_S}$ is calculated from the working equation^[6]

$$c = v \sqrt{-\frac{C_P}{C_V} \left(\frac{\partial P}{\partial v} \right)_T} \quad (20)$$

All the required values have been calculated. Substituting into Eq. (20) yields $c=147.164 \text{ (cm}^3\text{-bar/mol)}^{0.5}$. Since these

are unusual velocity units, some units conversion is in order. The average molecular weight of the vapor mixture is 67.152 g/mol and we find that the sonic velocity is

$$c^2 = 21657 \frac{\text{cm}^3\text{-bar}}{\text{mol}} \cdot 100000 \frac{\left(\frac{\text{kg-m}}{\text{s}^2} \right)}{\text{bar}} \frac{\text{m}}{100\text{cm}} \frac{1000\text{g}}{\text{kg}} \frac{1\text{mol}}{67.152\text{g}} = 3.2251 \times 10^8 \frac{\text{cm}^2}{\text{s}^2}$$

$$\text{or } c = 179.586 \text{ m/s} = 646.5 \text{ km/hr}$$

We can compare this result with the low pressure (ideal gas) limiting value

$$c_{\text{ID}} = \sqrt{\frac{C_P^{\text{ID}}}{C_V^{\text{ID}}} RT} = 185.683 (\text{cm}^3\text{-bar/mol})^{0.5} = 226.590 \text{ m/s}$$

DISCUSSION

Calculation of derivative properties is easy if there is an equation of state available to model the PVT behavior of the fluid. Two such properties have been evaluated here using the Peng-Robinson equation of state. It is trivial to evaluate a large number of other derivative properties once we know the three PvT derivatives and the two heat capacities. In this age of computers, it is worthwhile for the student to develop a spreadsheet or set of computer subroutines to calculate thermodynamic properties of hydrocarbons and hydrocarbon mixtures.^[7] Including these and other thermodynamic derivatives would be very easy, indeed.

It is interesting to estimate some of these derivatives by using their finite-difference approximations and to compare these estimates with results using the equations discussed above. For example, C_P is approximated by evaluating the enthalpy $H=H^{\text{ID}}+U^R+RT(Z-1)$ at two nearby temperatures at 11 bar (and same composition)

$$C_P \cong \left(\frac{\Delta H}{\Delta T} \right)_P = \frac{30012.449 - 29705.977}{391 - 389} = 153.236 \text{ J/mol-K}$$

which is essentially the same as the result obtained above, with any error due to the finite-difference approximation.

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COMPUTER MODELING IN THE UNDERGRADUATE UNIT OPERATIONS LABORATORY

Demonstrating the Quantitative Accuracy of the Bernoulli Equation

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The purpose of this experiment is to demonstrate the predictive capabilities of the Bernoulli equation in determining the time it takes a liquid to drain, under the influence of gravity, from a tank and through an exit pipe, as a function of initial tank charge, exit-pipe diameter, and exit-pipe length. The project is comprised of an experimental component and a modeling component.

In the modeling component, predictions of the efflux time are obtained from several different approximate solutions of the Bernoulli equation; in the experimental component, the flux time for water draining from a tank through various exit pipes is measured. Comparisons between the experimental and theoretical values are then made. The purposes of the comparison are

- ▶ *To evaluate which terms of the Bernoulli equation are important*
- ▶ *To test the limits of applicability of the Bernoulli equation*
- ▶ *To demonstrate the value of a rigorous computer modeling*

Descriptions of fluid-flow experiments appear in the literature. For example, Hesketh and Slater described an efflux from a tank experiment where students fit height-versus-time data, assuming there are no pressure losses within the system.^[1] In this work, we include head losses due to various friction terms. Hanesian and Perna described an experiment

in optimizing pipe diameter with respect to capital and operating costs.^[2] A key difference in the latter experiment is that the system was operating at steady state. In the experiment described here, efflux from a tank, there is no steady state, and thus the resulting equations are differential in nature.

EXPERIMENTAL SYSTEM

Our system is situated inside a cylindrical tank (tank radius = R_T) filled with water to height, H . The tank has a cylindrical pipe (pipe radius = R_P) of length L extending from the base of the tank (see Figure 1). The length and the diameter of the stainless steel exit pipe are variables depending on which of the eight available pipes is used. The pipe dimensions are given in Table 1.

The experimental apparatus is intentionally kept as simple as possible. When the students first see the tank and pipes, they frequently smirk and comment that the experiment is too “low-tech” to teach them anything of value, but through this experiment they learn that “The best experiment is the



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simplest experiment that still has enough guts to demonstrate the underlying physics of the system."^[3]

MATHEMATICAL MODEL

The mathematical model used to describe efflux from the tank is based on the mass and mechanical energy balances. If we define our system as the dotted line in Figure 1, and if we stop timing the efflux when the water level reaches H' , then the control volume is always full and we have a mass balance of the form

$$in = v_T A_T = v_T \pi R_T^2 = out = v_P A_P v_P \pi R_P^2 \quad (1)$$

assuming an incompressible fluid, where v_T is the flow average velocity in the tank, A_T is the cross-sectional area of the tank, and R_T is the radius of the tank. The subscript P designates analogous variables and parameters of the exit pipe. The average velocity of the fluid in the tank is defined as

$$v_T(t) = \frac{dH}{dt} \quad (2)$$

where t is time. Equation (2) can be substituted into Eq. (1) to yield an expression for the velocity in the pipe

$$v_P = \frac{dH}{dt} \frac{R_T^2}{R_P^2} \quad (3)$$

The mechanical energy balance (Bernoulli equation in-

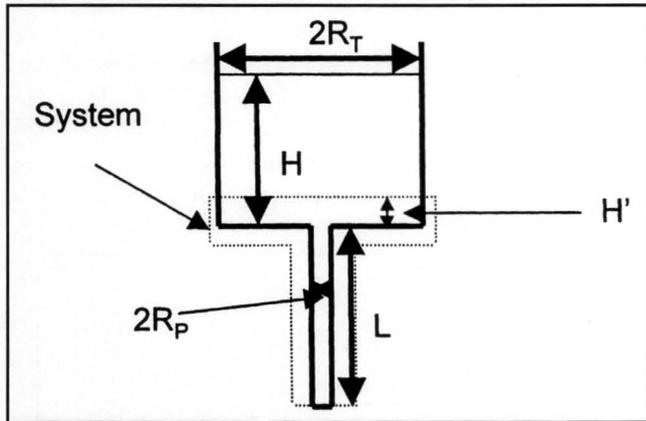


Figure 1. Schematic of the experimental apparatus.

TABLE 1 Pipe Dimensions	
Length (inches)	Inside Diameter (inches)
30	3/16
24	3/16
12	3/16
6	3/16
1	3/16
24	1/8
24	1/4
24	5/16

cluding friction terms) has the general form

$$\frac{g\Delta z}{g_c} + \frac{\Delta v^2}{2g_c} + \frac{\Delta P}{\rho} + \sum h_f = 0 \quad (4)$$

where g is gravity, $\Delta z = L + H'$, $\Delta v^2 = v_T^2 - v_P^2$, ΔP is the pressure drop, ρ is the density of the fluid, and h_f are the terms contributing to the head loss due to friction.

Again, if we define our system as the dotted line in Figure 1, we have the advantage that the accumulation term within the system over which the material and mechanical energy balance is drawn is zero, since the system is constantly full of liquid. This results in a non-zero pressure drop corresponding to the height of the water in the tank, less H' , the final height at which we stop the experiment.

In this system, we can consider frictional head loss due to the pipe wall, the contraction, and the tank wall

$$\sum h_f = h_{f, \text{pipewall}} + h_{f, \text{contraction}} + h_{f, \text{tankwall}} \quad (5)$$

We define each term in the Bernoulli equation

$$\Delta P = -\frac{\rho g(H - H')}{g_c} \quad (6)$$

The Darcy equation gives the friction head loss for flow in a straight pipe,

$$h_{f, \text{pipewall}} = 4 \left(\frac{f_p L}{D_p} \right) \frac{v_P^2}{2g_c} \quad (7)$$

where f_p is a dimensionless friction factor and D_p is the diameter of the pipe.^[4] If we assume turbulent flow in the pipe, we can obtain an estimate of the friction factor, f_p , using an empirical relation, known as the Blasius equation, applicable to turbulent flow with Reynolds numbers in the range of $4000 < N_{Re} < 100,000$.^[4]

$$f_p = \frac{0.0791}{N_{Re, P}^{0.25}} \quad (8)$$

The Blasius equation for a smooth pipe is used because it will allow for an analytical solution to the resulting differential equation. The friction loss due to contraction is given by^[5]

$$h_{f, \text{contraction}} = K_c \frac{v_P^2}{2g_c} = 0.5 \left(1 - \frac{D_P^2}{D_T^2} \right) \frac{v_P^2}{2g_c} \quad (9)$$

If we assume laminar flow in the tank, the friction loss due to the tank wall is

$$h_{f, \text{tankwall}} = 4f_T \left(\frac{H}{D_T} \right) \frac{v_T^2}{2g_c} = \frac{64}{N_{Re, T}} \left(\frac{H}{D_T} \right) \frac{v_T^2}{2g_c} \quad (10)$$

The assumption of turbulent flow in the pipe and laminar flow in the tank can be verified experimentally. For the diameters and lengths used in this experiment, these assumptions are confirmed.

If we combined Eqs. (1) through (10), we obtain a mechanical energy balance of the form^[6]

$$-g(L+H) + \left(\frac{dH}{dt}\right)^{1.75} \left[\frac{2(0.0791)\mu^{0.25}LD_T^{3.5}}{\rho^{0.25}D_P^{4.75}} \right] + \left(\frac{dH}{dt}\right)^2 \left[\frac{\left(\frac{D_T^4}{D_P^4}\right)^{-1}}{2} \right] + \frac{1}{4} \left(1 - \frac{D_P^2}{D_T^2}\right) \left[\frac{D_T^2}{D_P^2} \left(\frac{dH}{dt}\right) \right]^2 + \frac{32H\mu}{D_T^2\rho} \left(\frac{dH}{dt}\right) = 0 \quad (11)$$

Equation (11) is a first-order nonlinear ordinary differential equation. It has no known analytical solution.

If we rely on our engineering intuition to neglect terms of less significance, however, we might omit the kinetic energy term, the friction loss due to contraction, and the friction loss due to laminar flow in the tank. If we make these three assumptions, we will find that we can obtain an analytical solution to the resulting differential equation

$$t = \left[\frac{2(0.0791)\mu^{0.25}D_T^{3.5}}{g\rho^{0.25}D_P^{4.75}} \right]^{4/7} L \frac{7}{3} \left[\left(1 + \frac{H_0}{L}\right)^{3/7} - \left(1 + \frac{H(t)}{L}\right)^{3/7} \right] \quad (12)$$

where H_0 is the initial height of the water in the tank at time zero. Thus, we can find the time it takes for the water level in the tank to fall to a height, H , from the initial height, H_0 . This approximation is what is often used to describe the system in unit operations laboratories solely because it has an analytical solution. We will see in the next section, however, that this approximation gives not only quantitatively but also qualitatively incorrect results.

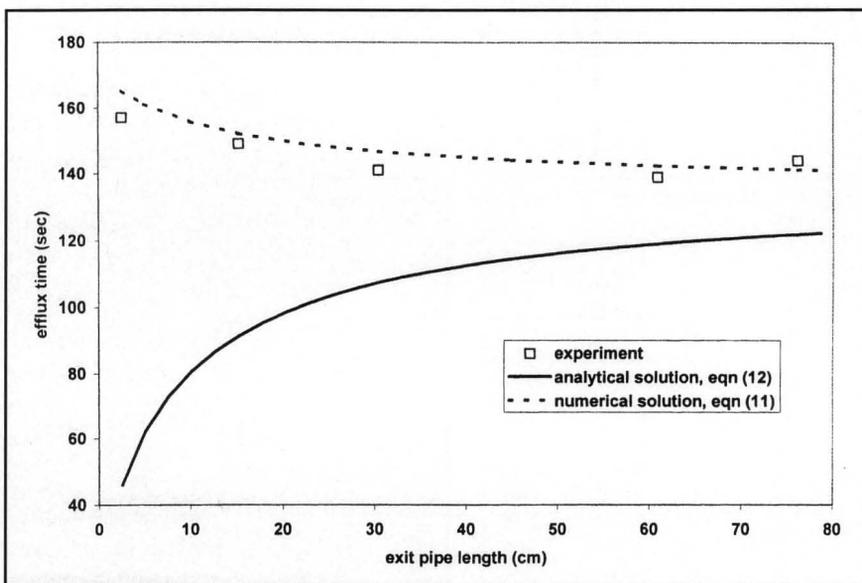
The more rigorous approach is to numerically solve the ordinary differential equation (ODE) in Eq. (11). We can use a standard numerical ODE-solution technique (*e.g.*, Euler's method or a Runge-Kutta method) if we can arrange the ODE into the form

$$\frac{dH}{dt} = f(H,t) \quad (13)$$

Equation (11) cannot be put in this form. Therefore, we cannot easily solve for the velocity in the tank, DH/dt , at every Euler or Runge-Kutta time step as is required by those algorithms. But for any given time, t , for which we know the height, H , we can obtain the numerical value of the tank velocity by using a technique to solve a single nonlinear algebraic equation, such as the Newton-Raphson method. Combining the Newton-Raphson and Runge-Kutta methods is a relatively simple algorithm to implement and involves nesting the iterative algebraic equation solver inside the routine that obtains the tank velocity for the ODE solver. For the undergraduates in the unit operations laboratory, we provide just such a routine, written for MATLAB.^[6] The students are familiar individually with the Runge-Kutta and Newton-Raphson techniques and the majority of them directly comprehend the combination of the two methods.

We have integrated the modeling component of this experiment with the curriculum-wide "Web Resource for the Development of Modern Engineering Problem-Solving Skills" instituted in the Department of Chemical Engineering at the University of Tennessee.^[7] This web resource acts as a stand-alone self-teaching module that students at any level in the program—from sophomores to graduate students—can access to obtain the basic algorithms to solve systems of linear algebraic equations, systems of nonlinear algebraic equations, systems of ordinary differential

Figure 2. Efflux time as a function of exit pipe length for the experimental case, the approximation to the mechanical energy balance with an analytical solution (Eq. 12), and for more complete mechanical energy balance, solved numerically (Eq. 11). The data are for water at 85°F draining from a six-inch diameter baffled tank from an initial height of 11 in. to a final height of 2 in. through a pipe with a nominal diameter of 3/16 in.



equations, numerical integration, and linear regression and analysis of variance.

EXPERIMENTAL RESULTS

In the lab the students examine the effects on efflux time of the initial water charge, the exit-pipe diameter, and the exit-pipe length. Here, we limit ourselves to the effect of the exit-pipe length. In Figure 2 we plot the flux time versus exit-pipe length for the experimental case, for the approximation to the mechanical energy balance with an analytical solution (Eq. 12), and for the complete mechanical energy balance, solved numerically (Eq. 11). The data are for water at 85°F draining from a six-inch diameter baffled tank from an initial height of 11 in. to a final height of 2 in. through a pipe with nominal diameter of 3/16 in. The water density and viscosity were obtained from the literature.^[8]

At short pipe lengths, we see that the experimental efflux time decreases with increasing pipe length, because gravity and the hydrostatic pressure term in Eq. (11) create a driving force for flow proportional to $(L+H)$. As we increase L , the driving force increases and the tank drains faster. In contrast, at longer pipe lengths, the experimental efflux time increases with increasing pipe length, because we have reached a point where skin friction due to the pipe wall is the dominating factor.

The approximation to the Bernoulli equation that has an analytical solution (Eq. 12) fails to model this behavior both qualitatively and quantitatively. The trend for Eq. (12) is a monotonic increase in efflux time with increasing pipe length. The average relative error of Eq. (12) with respect to the experimental data is 32.6%.

The more complete Bernoulli equation in Eq. (11) models the experiment both qualitatively and quantitatively. The average relative error of Eq. (11) with respect to the experimental data is 3.1%.

Plots have also been generated regarding the dependence of efflux time on pipe diameter and initial water height. Both the analytical solution (Eq. 12) and the numerical solution to Eq. (12) model the behavior qualitatively, namely that efflux time decreases as pipe diameter increases or initial water height decreases. But as was the case with the pipe length, the quantitative agreement is substantially better using Eq. (11).

CONCEPTUAL LESSONS OF THE EXPERIMENT

After the students have collected the experimental data in the laboratory, they take the data to the computer lab and model it using both Eqs. (11) and (12). Additionally, they look at variant models, adding one term at a time—kinetic energy, friction due to contraction, and friction due to the laminar flow in the tank wall. Adding the terms individually allows the student to determine the effect of each term in the

mechanical energy balance on the efflux time.

The students can also explore the comparison of experiment and theory in terms of error analysis. For example, they can calculate the Reynolds number at each experimental data point and show that for any given theoretical model the accuracy decreases as the Reynolds number drops and reaches the lower limit of applicability of the expression used for the turbulent friction factor.

Finally, the students (primarily juniors) obtain a first-hand demonstration of the quantitative accuracy of the Bernoulli equation. The experience helps them understand the significance, validity, and limitations of the otherwise abstract mathematical expressions with which they are presented in classroom lectures on fluid flow.

CONCLUSIONS

In this work we have described a very simple efflux from a tank experiment, of the sort commonly employed in undergraduate unit operations laboratory courses. We have shown that relying only on a simplified analytical solution to the Bernoulli equation not only fails to quantitatively model the experimental results but also qualitatively fails to capture the correct trends. We have provided a more complete mechanical energy balance, outlined its numerical solution, and shown that it both qualitatively and quantitatively models the experiment.

The inclusion of a computer simulation in the experiment allows the students to demonstrate for themselves the consequences of over-simplified engineering approximations and the value of a rigorous mathematical model.

ACKNOWLEDGMENTS

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2001 ASEE Annual Conference

Chemical Engineering Division Program

June 24 - 27, 2001 • Albuquerque, New Mexico

Technical Sessions

Monday, June 25

Session 1313 • 10:30 a.m. • Capstone Design Issues in Chemical Engineering

Moderators: Chris Wiegenstein and David Miller

1. "Capstone Chemical Engineering Laboratory Courses at Michigan Tech"
A.J. Pintar, E.R. Fisher, and K.H. Schulz
2. "Open Beginning Projects: A Flexible Approach to Encouraging Student Curiosity and Creativity"
S.S. Moor
3. "A Hands-On Multidisciplinary Design Course for Chemical Engineering Students"
J.M. Keith, D. Charu, J. Meyer, and N. Norman
4. "The Inclusion of Design Content in the Unit Operations Laboratory"
D. Ridgway, V.L. Young, and M.E. Prudich
5. "An Introduction to Process Simulation for the Capstone Design Course"
D. Miller, T.N. Rogers, and B.A. Barna
6. "Graduate Bridging and Continuing Education in Chemical Engineering via the Web"
R.M. Worden, D. Briedis, and C.T. Lira

Session 1413 • 12:30 p.m. • Non-Traditional Topics in Chemical Engineering

Moderators: Nada Assaf-Anid and Ann Marie Flynn

1. "Introducing Emerging Technologies into the Curriculum Through a Multidisciplinary, Industrially-Sponsored Research Experience"
J.A. Newell, S.M. Farrell, R.P. Hesketh, and C.S. Slater
2. "Integration and Use of a Novel Semiconductor Processing Simulator to Teach Stream Recycle Issues to Chemical Engineering Students"
P. Blowers and E. Weisman
3. "A Course on Health, Safety, and Accident Prevention"
A.M. Flynn, J. Reynolds, and L. Theodore
4. "Training Chemical Engineers in Bioprocessing"
C. Preston, D. Briedis, and R.M. Worden
5. "Biotechnology and Bioprocessing Laboratory for Chemical Engineering and Bioengineering"
S. Sharfstein and P. Relue
6. "Bacterial Disinfection in the Classroom: Engineering-Based Experimental Design"
N.M. Assaf-Anid

Tuesday, June 26

Session 2213 • 8:30 a.m. • Laboratory Automation and Classroom Demonstrations

Moderators: Connie Hollein and Jim Henry

1. Laboratory Remote Operation: Features and Opportunities"
J.M. Henry
2. "Using Web-Based Supplemental Instruction for Chemical Engineering Laboratories"
C.R. Nippert
3. "Virtual Reality Laboratory Accidents"
J.T. Bell and H.S. Fogler
4. "Exercise in Chemical Engineering for Freshmen"
S.M. Farrell and R.P. Hesketh
5. "Teaching Chemical Engineering with Physical Plant Models"
K.H. Pang
6. "Engineering Experiments Utilizing an Automated Breadmaker"
R.P. Hesketh, C.S. Slater, and C.R. Flynn
7. "Utilizing Experimental Measurements to Introduce Underrepresented Pre-College Students to Science and Engineering"
A. Perna and D. Hanesian

Session 2565 • 2:30 p.m. • Math Requirements in the Chemical Engineering Curriculum

Moderators: Anton Pintar and Jenna Carpenter

1. "Mathematics and Chemical Engineering Education"
A. Pintar, F. Carpenter, M. Cutlip, M. Graham, and J. Puszynski
2. "Mathematics in Chemical Engineering: From the 'Ball-Park' to the 'Lap-Top'"
R. Toghiani and H. Toghiani

Session 2613 • 4:30 p.m. • A Galaxy of Stars

Moderators: David Kauffman and Melanie McNeil

Senior chemical engineering faculty who have been leaders in the analysis, development, and dissemination of educational techniques will be members of a panel to discuss the current state of chemical engineering education and how it has progressed, or digressed, over the past three decades, and how it will change in the coming decades. They will introduce "rising stars" in the field, who will also participate in the panel discussion. Senior panel members include Richard Felder, James Stice, and Billy Crynes.

Wednesday, June 27

Session 3213 • 8:30 a.m. • The Latest in Pedagogy in Chemical Engineering

Moderators: Joe Shaeiwitz and Wallace Whiting

1. "The Role of Homework"
P. Wankat
2. "Using Critical Evaluation and Peer-Review Writing Assignments in a Chemical Engineering Process Safety Course"
D.K. Ludlow
3. "Criterion-Based Grading for Learning and Assessment in the Unit Operations Laboratory"
V.L. Young, M.E. Prudich, and D.J. Goetz
4. "Mid-Semester Feedback Enhances Student Learning"
R. Wickramasinghe and W.M. Timpson
5. "Development and Implementation of a Computer-Based Learning System in Chemical Engineering"
N.L. Book, D.K. Ludlow, and O.C. Sitton
6. "Evaluation of IT Tools in the Classroom"
S. Soderstrom and C. Lorenz

Session 3413 • 12:30 p.m. • The Master as the First Professional Degree

Moderator: David Kauffman

There is a great deal of discussion concerning the need for a more-than-four-year program for the first professional level in engineering. A panel of experts will give background information and discuss issues raised by the audience. Panelists include Thomas Hanley, Gerald May, and Paul Penfield.

Session 3513 • 2:30 p.m. • Computers and Computation in the Chemical Engineering Curriculum

Moderators: Annetta Razatos and Donald Visco

1. "Template-Based Programming in Chemical Engineering Courses"
D.L. Silverstein
2. "Sealing Analysis—A Valuable Technique in Engineering Teaching and Practice"
E.M. Kopaygorodsky, W.B. Krantz, and V.V. Gulians
3. "Is Process Simulation Effectively Utilized in Chemical Engineering Courses?"
M.J. Savelski, K.D. Dahm, and R.P. Hesketh
4. "Scientific Visualization for Teaching Thermodynamics"
K.R. Jolls
5. "Integrating Best Practice Pedagogy with Computer-Aided Modeling and Simulation to Improve Undergraduate Chemical Engineering Education"
J.L. Gossage, C.L. Yaws, D.H. Chen, K. Li, T.C. Ho, J. Hopper, and D.L. Cocke

Society-Wide Picnic
Sunday, June 24, 5:00 p.m.
National Atomic Museum

ChE Division Lectureship
Monday, June 25, 4:30 p.m.
Moderator: Doug Hirt
Speaker to be announced

ChE Division Awards Banquet
Monday, June 25, 6:30 p.m.
Albuquerque Petroleum Club
Speaker to be announced

Meet the ASEE Board
Breakfast
Tuesday, June 26, 7:00 a.m.

ChE Division Business
Luncheon
Tuesday, June 26, 12:30 p.m.

ASEE Annual Reception
and Awards Banquet
Wednesday, June 27, 6:00 p.m.

USING IN-BED TEMPERATURE PROFILES FOR VISUALIZING THE CONCENTRATION-FRONT MOVEMENT

PAULO CRUZ, ADÉLIO MENDES, FERNÃO D. MAGALHÃES
University of Porto • 4200-465 Porto, Portugal

Purification of gas streams through adsorption in a packed column is an important process in chemical engineering. The experimental study of such systems involves determination of breakthrough curves for the adsorbable components in the column. Both theoretical and practical implementations of this process are common in undergraduate courses, but students do not readily assimilate some of its aspects. The retention of a concentration front in an adsorbent bed and its implications on the formation of shock waves, for instance, are not easy to visualize mentally, especially when experimental information concerns only the outlet concentration history.

In our senior undergraduate laboratory, we have developed an experiment that has been successful in helping students grasp the concepts of concentration-front movement in fixed beds. Due to the structure of the curricular program, most students actually take this lab course before the advanced separation course in which the theory associated with these processes is detailed. This does not seem to impair the students' ability to interpret and understand the experimental results and theoretical concepts, however.

In addition to the measurement of the outlet breakthrough curve, a set of thermocouples within the bed allows for the indirect "visualization" of the advancement of the concentration front.

A process simulation program, developed for this purpose, also lets students gain sensitivity for the relative importance of the different operation parameters and physical properties. This easy-to-use software is available for downloading at

<http://raff.fe.up.pt/~lepae/simsorb.html>

In this paper we start by briefly describing the Solute Movement Theory, which is a basic tool for interpreting this kind of process, and the mathematical model used in the

software simulation, which involves a more detailed description. Later we will illustrate how students can use both in the interpretation of experimental results.

THEORETICAL BACKGROUND

A certain gas, A, diluted in an inert carrier gas stream travels in a column packed with a non adsorbent solid at the same velocity as the carrier. If, however, the solid adsorbs gas A, then its velocity will be lower than the carrier's. Simply put, the gas is "retained" by the solid, *i.e.*, it cannot proceed along the column while the adsorption sites are not filled. This idea is more-or-less simple and intuitive.

Things become a bit more complicated, though, when one tries to interpret phenomena such as the formation of different kinds of concentration-front waves. This is when the Solute Movement Theory (SMT) comes in handy. It predicts (for simplified but meaningful conditions) the solute velocity as a function of concentration. Its main result states that an infinitesimal element of solute, with concentration c_A , will travel the column at a velocity u_s , which depends (inversely) on the slope of the adsorption isotherm for c_A (dq_A/dc_A)

$$u_s = \frac{v}{1 + \rho \frac{1 - \epsilon}{\epsilon} \frac{dq_A}{dc_A}} \quad (1)$$

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Adélio Mendes received his licentiate and PhD from the University of Porto, Portugal, where he is currently Associate Professor. He teaches chemical engineering laboratories and separation processes. His main research interests include membrane and sorption gas separations.

Fernão Magalhães is Assistant Professor of Chemical Engineering at the University of Porto, Portugal. He received his PhD from the University of Massachusetts in 1997. His research interests involve mass transport and sorption in porous solids and membranes.

where v is the interstitial velocity of the inert carrier gas, ϵ is the packing porosity, ρ is the adsorbent's apparent density, and q_A is the concentration of A adsorbed in the solid, in equilibrium with c_A . The reader can find the details of our approach for deriving Eq. (1), based on a differential mass balance to the column, at

<http://raff.fe.up.pt/~lepae/simulator.html>

For other approaches see, for example, the book by Wankat.^[1]

SMT implies, of course, a series of simplifying assumptions, the major being

1. local adsorption equilibrium
2. plug flow in gas phase
3. negligible pressure drop along the column
4. isothermal operation
5. low adsorbate concentration

Assumptions 4 and 5 imply that the interstitial gas velocity can be assumed constant.

It is quite clear, from Eq. (1), that stronger adsorption (higher dq_A/dc_A) implies slower solute movement (lower u_s). On the other hand, if there is no adsorption, then $u_s = v$, and the solute moves at the same speed as the inert carrier gas.

Let us now consider that the column, initially without solute, is subject to an inlet concentration step of magnitude c_2 . Suppose that two well-defined linear regions, as shown in Figure 1, compose the adsorption isotherm for this solute.

Solute elements with concentrations between 0 and c_1 will, according to Eq. (1), have a velocity

$$u_{s1} = \frac{v}{1 + \rho \frac{(1-\epsilon) q_1}{\epsilon c_1}} \quad (2)$$

On the other hand, for solute elements with concentrations between c_1 and c_2 the velocity is

$$u_{s2} = \frac{v}{1 + \rho \frac{(1-\epsilon) (q_2 - q_1)}{\epsilon (c_2 - c_1)}} \quad (3)$$

Velocity u_{s1} is lower than u_{s2} . Due to the particular shape of the isotherm, high concentrations tend to move faster than low ones. This would apparently lead to the situation de-

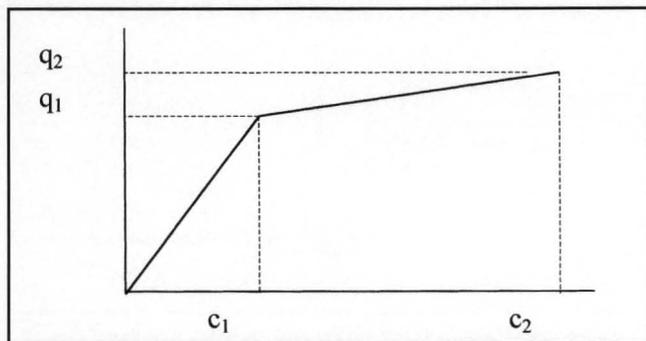


Figure 1. Idealized adsorption isotherm.

picted in Figure 2: high concentrations moving ahead of low concentrations!

This is obviously a physical impossibility. High concentrations cannot exist without the lower ones. What actually occurs is the formation of a shock wave. The concentration front shown on the left in Figure 2 preserves its shape as it moves along the column, with a velocity intermediate between u_{s1} and u_{s2} . This velocity can be derived from a mass balance to the shock wave, the result being

$$u_s = \frac{v}{1 + \rho \frac{1-\epsilon}{\epsilon} \frac{q_2}{c_2}} \quad (4)$$

As will be shown later, dispersion effects (not accounted for in SMT) cause the concentration front to develop some distortion as it moves along the column.

And what will happen in the case of desorption, *i.e.*, when, assuming the same isotherm, a negative concentration step is applied at the column entrance (Figure 3)?

Once again, the higher concentrations (between c_1 and c_2) tend to move faster. But now these can actually move ahead of the lower ones, causing a progressive deformation of the originally sharp concentration front. We have, then, a dispersive or diffusive wave.^[1]

This discussion can be easily extended to the analysis of more realistic systems, where the adsorption equilibrium is described by, say, a Langmuir-type isotherm. Such isotherms, where dq/dc decreases with increasing c , are called favorable isotherms. It is easy to understand that in the opposite case, *i.e.*, for an unfavorable isotherm, the conditions discussed here for the formation of shock and diffuse waves would be reversed.

The way SMT describes adsorption in a packed column is quite simplistic. More realistic considerations, such as axial

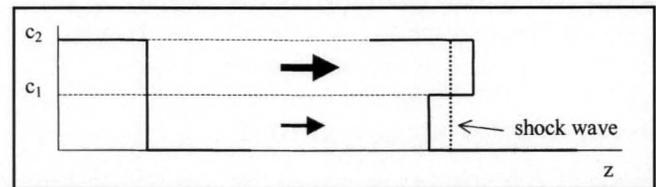


Figure 2. Hypothetical progression of a step in concentration, corresponding to the isotherm shown in Figure 1. This is the basis for the formation of shock waves.

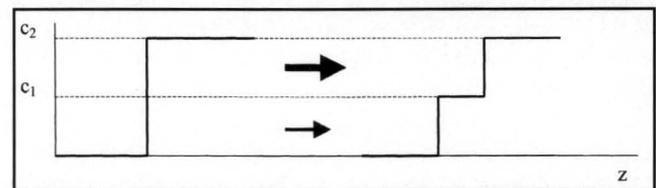


Figure 3. Hypothetical progression of a negative step in concentration, corresponding to the isotherm shown in Figure 1. This would be a dispersive wave.

dispersion, intra-particle mass transport resistance, and non-isothermal behavior, can be added if one establishes a more complex mathematical model for this process. The differential mass and energy balances of our “complex model” (CM) are presented in the Appendix.

Students are expected to be able to interpret each term in the balance equations, even though the resolution of a system of partial differential equations is beyond their abilities. For that we supply our homemade software *simsorb*, which uses finite difference discretization of the spatial coordinate (routine PARSET from package FORSIMVI) and performs the time integration with routine LSODA. It uses a MS-Excel interface for inputting the data and for plotting the results. This software is available for downloading at

<http://raff.fe.up.pt/~lepae/simsorb.html>

The input spreadsheet already contains the set of physical parameters and operating conditions used in simulating our experimental results. The adsorption isotherms (of the type Langmuir-Freundlich) were experimentally measured at our lab and the Peclet number (axial dispersion) estimated from an available correlation.^[2] Values for the global heat-transfer coefficient and the intra-particle diffusion coefficient were not measured directly. They were obtained by fitting the model to experimental results. This is done previously by the class tutor, so when the students run the simulator for the first time they observe a good agreement between the model’s output and their experimental results. Students can later run the simulator with other input data and analyze its effects on the system’s performance. An example of this is given later in this paper.

INTERPRETING EXPERIMENTAL RESULTS

The previous theoretical introduction is essentially the first contact that students have with Solute Movement Theory. Even if they seem to understand it relatively well, the sedimentation of concepts demands a more tangible, *i.e.*, experimental, approach. Ideally, it would be possible to directly observe the evolution of a concentration front within a packed column. This is, of course, not the case. Only inlet and outlet concentrations are, in principle, accessible. By measuring the temperature at different points in the column’s axis, however, one can obtain indirect information on the behavior of the concentration front along it.

One may point out that the existence of measurable thermal effects is certainly contrary to the SMT’s original hypothesis of isothermal operation. Nonetheless, as long as these are not excessive, a good compromise

can be obtained between the applicability of SMT and an “on-line visualization” of the progress of the concentration front, as we shall see.

For our lab course we use the adsorbate/adsorbent pair CO₂/activated carbon. Carbon dioxide was chosen since, in addition to being quite safe to work with and having a low cost, it has a high heat of adsorption in activated carbon. We used activated carbon from Chemviron Carbon in the form of extruded pellets (6.3 mm x 3.6 mm).

Our setup is shown schematically in Figure 4. The column is 250 mm long and 50 mm in internal diameter. Seven evenly spaced holes were drilled in its side to allow for insertion of the thermocouples. The column is placed inside an oven. This has a twofold purpose: to keep the surrounding temperature constant (the oven is set to a temperature slightly above room temperature) and to allow for complete regeneration if necessary. Actually, we noticed that for this system (CO₂/activated carbon), high-temperature regeneration is not needed; pure helium flow at operation temperature suffices for removing the adsorbed CO₂ (within the sensor’s detection limit). The inlet flow rates of helium (the carrier gas) and carbon dioxide are controlled with two needle valves and monitored with electronic flow meters. The outlet concentration of carbon dioxide is measured with an infrared CO₂ sensor. The inlet feed concentration can be checked before starting a run by directing the feed into the sensor through a column by-pass. A data-acquisition system connected to a computer allows for continuous visualization and, if desired, storage of all data (flow rates, temperature, composition).

Students are asked to perform two breakthrough experiments:

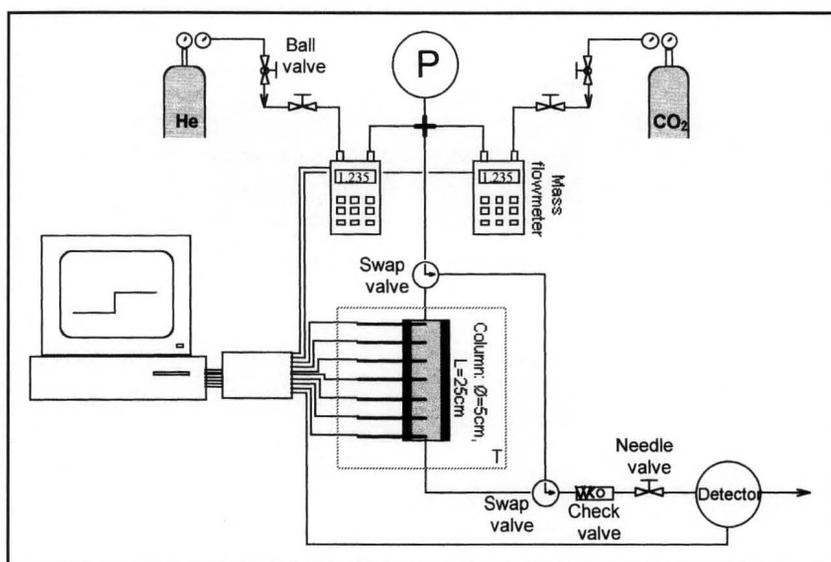


Figure 4. Experimental setup for breakthrough experiments with in-bed temperature measurement.

1. Response to a positive concentration step at the inlet (from pure helium to about 5% mol fraction CO_2)
2. Response to a negative concentration step at the inlet (from 5% CO_2 back to pure helium) after stage 1 has reached steady state.

Complete execution time is about 1.5 hours, leaving enough time for the students to plot the data in the computer and start analyzing the results.

As an example, we next provide some typical plots obtained for the operating conditions listed in Table 1.

The breakthrough curve (*i.e.*, the history of the CO_2 concentration measured at the column's outlet) obtained for a positive concentration step is shown in Figure 5.

As discussed previously, SMT predicts, for a positive inlet step and a favorable isotherm, the formation of a shock wave (a sharp vertical front). On the other hand, the experimental curve shows a notorious tilt and rounded edges. It is actually noticeable—a pronounced “tailing” as the front approaches the steady-state concentration. This departure from “ideality” is associated with dispersion effects that oppose the compressive nature of the front, such as axial dispersion, intra-particle mass transfer resistance, and non-isothermality. Students are asked to identify and discuss these phenomena. By using the software simulator, they will actually be able to identify the predominant dispersive effect in this case.

TABLE 1
Operating Conditions

Operation Temperature (°C)	Ambient Pressure (Pa)	Operation Pressure (Pa)	Helium Flowrate ($\text{m}^3(\text{PTN})/\text{s}$)	Carbon Dioxide Flowrate ($\text{m}^3(\text{PTN})/\text{s}$)
38.1	1.00×10^5	2.60×10^5	4.35×10^{-5}	2.48×10^{-6}

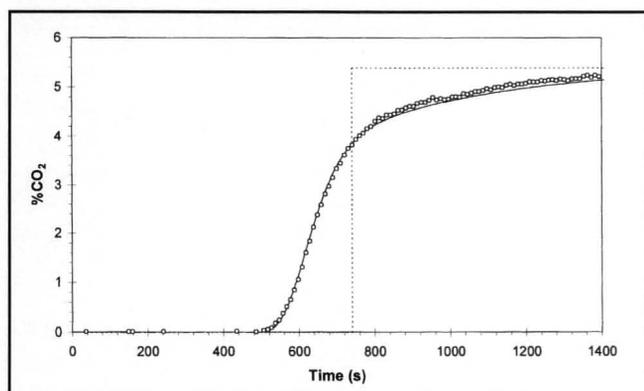


Figure 5. Breakthrough curve (exit CO_2 mol fraction as a function of time) for a positive concentration step at the inlet. The solid line refers to the fit of the complex model. The dashed line is the result from Solute Movement Theory: an ideal shock wave with breakthrough time computed from Eq. (4).

Figure 6 shows the corresponding temperature histories along the column. Data from the last thermocouples are not shown since they are placed at the beginning and at the end of the packed bed where heat is being dissipated through the column's inlet and outlet flanges. This effect masks the temperature information provided by the two thermocouples. Thermocouples 2 and 6, on the other hand, depict quite well the progress of the concentration front along the column.

The observed increase in temperature is associated with the exothermal adsorption of CO_2 at the concentration front. The significant amplitude of the temperature increase (about 7°C), as well as the long length of time that it takes for cooling down, usually surprises the students. It is a good way to make them start questioning the validity of the isothermality hypothesis, often applied without proper reflection in chemical engineering problems.

A more subtle observation is associated with the successive broadening of the temperature peaks along the column or, more clearly visible, the decrease in the temperature maximum measured in each thermocouple. Note: the second peak shown in Figure 6 was recorded with a slightly different thermocouple and therefore it has a different response time. Aside from this deviation from the general trend, one may then conclude that this broadening is associated with the increasing dispersion of the concentration front as it travels along the column. Eventually, the dispersive and compressive effects compensate each other at some point in the column and the shape of the front stabilizes. This is the so-called constant pattern regime.^[1]

Despite the clear evidences of non-isothermality and dispersive effects, students are asked to use SMT (more exactly, Eq. 4) to predict the time it takes for the shock wave to reach each thermocouple and to compare this with the experimental results, using the maximum temperature in each peak as a reference for the passage of the concentration front. Note that (for such a comparison to be meaningful) we have

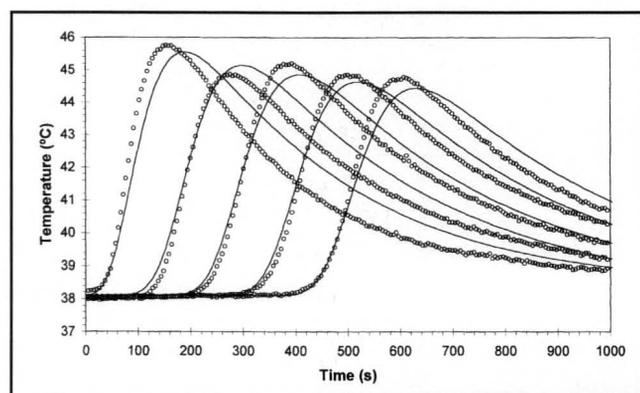


Figure 6. Temperature histories obtained at evenly spaced points inside the column, for a positive concentration step at the inlet. The solid lines refer to the fit of the complex model.

to assume that the temperature front travels in combination with the concentration front. Under some conditions (mainly for adiabatic systems), the temperature front may lead the concentration front.^[3] The reasonability of our assumption is reinforced by comparing simulated concentration and temperature profiles. In addition, as can be seen from Table 2, there is a good agreement between the SMT estimations and the experimental results. It is remarkable that the simple SMT model still seems to have some predictive value under these operating conditions.

In relation to the desorption step, the resulting breakthrough curve is shown in Figure 7. SMT predicts that a negative concentration step associated with a favorable isotherm leads to a diffuse wave. The presence of other dispersion phenomenon adds to this effect, causing the experimental concentration front to have a very pronounced tilt.

Figure 8 shows the temperature history profiles. The peaks are now inverted, since desorption is an endothermic process. Now there is a clear broadening of the peaks as the front travels along the column, agreeing with its dispersive nature (in addition to the aforementioned dispersion phenomena).

The qualitative differences between the results obtained from the positive and negative steps are quite evident to the students and contain a lot of material for discussion. The quantitative analysis in terms of SMT is also quite interesting. In addition, students are asked to run the simulation program and to compare its results to the experimental data (see Figures 5 to 8 and Table 2). The complex model, by considering several dispersion effects and non-isothermality, is able to reproduce quite nicely the shapes of the breakthrough curves and temperature peaks.

Students are encouraged to run the simulator with other input parameters and therefore gain sensitivity to how these affect the results. It is particularly interesting to study those

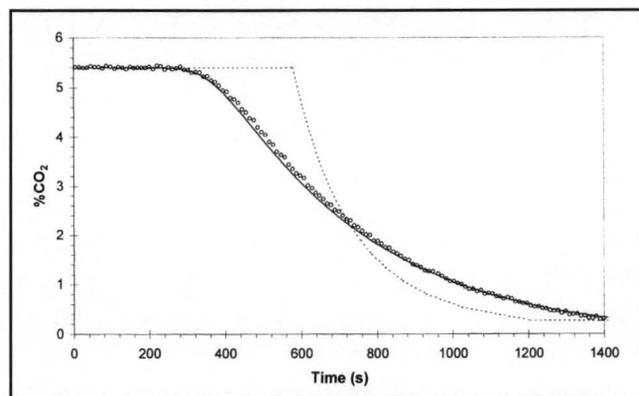


Figure 7. Breakthrough curve (exit CO_2 mol fraction as a function of time) for a negative concentration step at the inlet. The solid line refers to the fit of the complex model; the dashed line is the result from Solute Movement Theory, with breakthrough times for each concentration computed from Eq. (1).

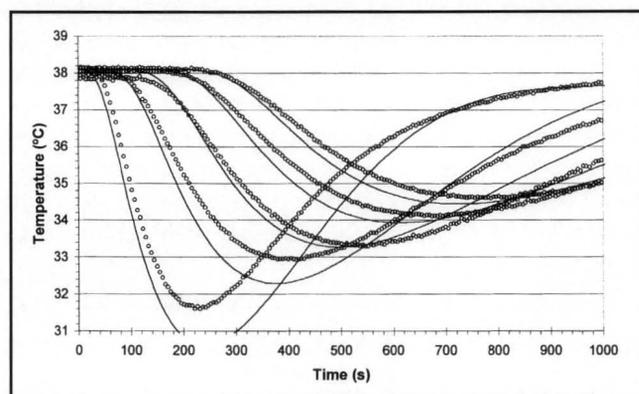


Figure 8. Temperature histories obtained at evenly spaced points inside the column for a negative concentration step at the inlet. The solid lines refer to the fit of the complex model.

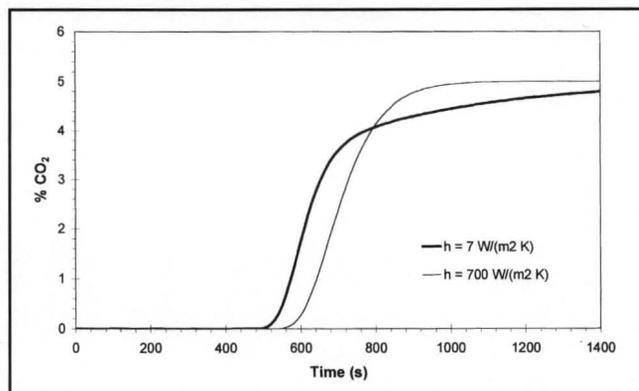


Figure 9. Breakthrough curves obtained with the complex model for two different values of the global heat-transfer coefficient, h . The value $h=7\text{W}/(\text{m}^2\text{K})$ is the one used in fitting the experimental data (Figures 5 to 8). The value $h=700\text{W}/(\text{m}^2\text{K})$, on the other hand, is equivalent to assuming that heat transfer to the exterior is instantaneous.

TABLE 2

Time for the Concentration Front to Reach Each Thermocouple Position

The experimental time refers to the time when the maximum temperature is reached, the theoretical time from SMT uses Eq. (4), and the theoretical time from CM uses the results from the complex model simulations.

Thermocouple position (m)	Experimental time (min)	Theoretical time from SMT (min)	Theoretical time from Cm (min)
0	-	0.0	0
0.042	3.0	2.1	2.3
0.083	4.8	4.2	4.2
0.125	6.6	6.3	6.2
0.167	8.4	8.4	8.3
0.208	10.3	10.4	10.5
0.250	12.1	12.5	12.5

parameters that are probably more difficult (or impossible) to change experimentally, such as the global external heat transfer coefficient, the heat of sorption, or the intra-particle mass-transfer coefficient. For example, increasing the global heat-transfer coefficient gives rise to a quite different breakthrough curve (see Figure 9). The outlet concentration front is now much closer to a perfect sigmoid, approaching steady state much more rapidly. This seems to indicate that heat accumulation inside the column is the major cause for the "tailing" of the breakthrough curve. As the front passes, the temperature rises significantly, and the amount adsorbed is lower than for isothermal operation. As the column cools down again, the adsorption equilibrium is shifted toward the adsorbed state and more CO₂ is retained in the column. The consequence is that the outlet concentration will take longer to reach steady state.

In addition to complementing the discussion of the results, using the simulation program has an extra pedagogic purpose: it shows students how process modeling in general can be useful in helping to understand and optimize a real system.

CONCLUDING REMARKS

The experimental study of adsorption in packed beds can be complemented if, in addition to measuring the outlet breakthrough curves, one obtains the temperature histories in different points along the bed. Such an experimental setup is quite simple and economic and provides valuable qualitative and quantitative information that students can process without major difficulties. Solute Movement Theory is a basic tool for that analysis. In addition, using a software simulator based on a more detailed mathematical model provides a better description of the process and allows students to perform "virtual" experiments and understand how different factors

influence the behavior of the adsorption system.

ACKNOWLEDGMENTS

The authors wish to thank the Chemical Engineering Department for providing financial support for the setup of this experiment.

NOMENCLATURE

c_A	concentration of A in the inter-particle gas phase (mol/m ³)
C_{p_g}	heat capacity of gas (J/mol/K)
C_{p_s}	heat capacity of adsorbent (J/kg/K)
D_{ax}	axial dispersion coefficient (m ² /s)
D_i	intra-particle diffusion coefficient (m ² /s)
h	overall heat-transfer coefficient (J/m ² /K/s)
P	pressure (Pa)
q_A	concentration of A adsorbed in the solid (mol/kg)
\bar{q}_A	average concentration of A adsorbed in the solid (mol/kg)
R_b	bed radius (m)
r_p	particle radius (m)
t	time (s)
T	temperature (K)
u_s	interstitial solute velocity (m/s)
v	interstitial carrier gas velocity (m/s)
z	axial coordinate (m)

Greek Letters

ΔH	heat of adsorption (J/mol)
ϵ	packing porosity
\mathfrak{R}	gas constant
ρ	adsorbent's apparent density

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2. Edwards, M.F., and J.F. Richardson, "Gas Dispersion in Packed Beds," *Chem. Eng. Sci.*, **23**, 109 (1968)
3. Yang, R.T., *Gas Separation by Adsorption Processes*, Imperial College Pres, London, pp. 161-165 (1997) □

APPENDIX

The main assumptions of the model are:

1. Plug flow with axial dispersion
2. Negligible radial gradients
3. Negligible pressure drop
4. Variable interstitial velocity
5. Instantaneous thermal equilibrium between stationary and mobile phases
6. Negligible thermal axial dispersion
7. Constant heat capacities
8. Intra-particle mass transport described by linear driving force model
9. Negligible film mass transfer resistance
10. Helium does not absorb
11. No heat accumulation at the wall

Global mass balance (where the total concentration has already been rewritten as a function of total pressure - assumed constant - and

temperature):

$$\frac{\partial v}{\partial z} - \frac{v}{T} \frac{\partial T}{\partial z} + D_{ax} T \frac{\partial}{\partial z} \left(\frac{1}{T^2} \frac{\partial T}{\partial z} \right) - \frac{1}{T} \frac{\partial T}{\partial t} + \frac{\mathfrak{R}T}{P} \frac{1-\epsilon}{\epsilon} \rho \frac{\partial \bar{q}_A}{\partial t} = 0 \quad (A1)$$

Inter-particle solute mass balance

$$\frac{\partial (vc_A)}{\partial z} - D_{ax} \frac{\partial^2 c_A}{\partial z^2} + \frac{\partial c_A}{\partial t} + \frac{1-\epsilon}{\epsilon} \rho \frac{\partial \bar{q}_A}{\partial t} = 0 \quad (A2)$$

Intra-particle solute mass balance (using the linear driving force model)

$$\frac{\partial \bar{q}_A}{\partial t} = \frac{15D_i}{r_p^2} (q_A - \bar{q}_A) \quad (A3)$$

Energy balance

$$\epsilon \frac{P}{\mathfrak{R}T} v C_{p_g} \frac{\partial T}{\partial z} + \left[\epsilon \frac{P}{\mathfrak{R}T} C_{p_g} + \rho(1-\epsilon)C_{p_s} \right] \frac{\partial T}{\partial t} - \Delta H \rho(1-\epsilon) \frac{\partial \bar{q}_A}{\partial t} + \frac{2h}{R_b} (T - T_a) = 0 \quad (A4)$$

Student-Performance Enhancement by CROSS-COURSE PROJECT ASSIGNMENTS

A Case Study in Bioengineering and Process Modeling

GÜLNUR BIROL, İNANÇ BIROL, ALI ÇINAR
Illinois Institute of Technology • Chicago, IL 60616

A wide range of practical, industrial, and medical applications has increased the demand for “bio-related” courses in the university curriculum. Students from biology, chemical engineering, and electrical engineering departments, all with different interests and expectations, enroll in these courses. Due to the diverse nature of the population in such classes, a variety of educational approaches and tools are necessary, both for accumulating knowledge and for implementing the theory.

The typical undergraduate student takes four or five courses per semester, but for many students this load may become too difficult to handle because of all the assignments, projects, and midterm examinations. From time to time, this necessitates a trade-off among the tasks in the “to-do list.” This need led us to initiate a cross-course platform that offered a joint term project to those students taking the “Introduction to Bioengineering” (IB) and “Process Control” (PC) courses. With this initiative, we tested the hypothesis that integrating cross-course concepts in bioengineering and process control courses through a unified project could provide a stimulating learning environment. The integrated project would also challenge the students to think beyond each course in an isolated manner.

BACKGROUND

Biotechnology/biomedical engineering courses at the undergraduate and graduate levels are offered regularly in the Chemical and Environmental Engineering Department at the Illinois Institute of Technology. Among the undergraduate-level courses, “Introduction to Bioengineering” provides an introductory knowledge of biotechnology and biomedical

engineering from a chemical-engineering point of view. One-half of the semester is spent on biomedical engineering, while the other half is used for biochemical engineering. Topics covered in the course are listed in Table 1.

Typically, two-thirds of the IB class population has a strong interest in biomedical engineering, while one-third is interested in biotechnology. The department offers a biomedical specialization program, and students interested in



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. . . we tested the hypothesis that integrating cross-course concepts in bioengineering and process control courses through a unified project could provide a stimulating learning environment.

careers in medicine and in the medical industries are expected to take this course. Many undergraduate students who take the IB course register concurrently for the PC course since it is a senior-year core course. Some students take the PC in their sixth semester to avoid potential conflicts in their schedules. Table 2 shows the content of the PC course.

There are roughly 10-15 students who register for the IB course each semester, while 25-35 students register for the PC course. In both courses, homework assignments are usually given on a weekly basis and form 20% of the course grade. Students are encouraged to discuss the problems and to exchange ideas with the instructors and teaching assistants. Since the number of students is relatively low, it gives them an opportunity to interact with the course instructors on a one-to-one basis.

In the IB course, the homework assignments are theory-intensive and can be solved using a calculator or an Excel worksheet, while in the PC course, homework problems are computation-intensive and knowledge of Matlab is required to solve them. In order to have a uniform student profile in Matlab competence, the instructor tutors introductory topics in a computer-laboratory environment, holds office hours in a computer lab, and assigns study hours under the supervision of the teaching assistant. Furthermore, supplementary web-based tutorial material about Matlab and a troubleshooting service on the source codes are provided through the Internet.

SCOPE

We wanted to form a cross-course platform where students could use their knowledge from two different fields—bioengineering and process control—emphasizing the use of common tools from process dynamics, differential equations, and computer simulations. Concentrating on a unified project, students would then have an opportunity to analyze the results from a wider perspective.

To that end, glucose-insulin interaction was chosen as the model system to be investigated. Its dynamic behavior is interesting for process modeling and control, and the unique interactions taking place in various organs in the body are of importance in bioengineering. The choice of this model system turned out to be a very attractive project in both courses. Students were quite interested in the project, both because of its academic impact and because of the challenges that it offered in investigating a real-life problem. All of the bioengi-

TABLE 1
Course Contents: "Introduction to Bioengineering"

■ *Part I: Biomedical Engineering*

- The History of Biomedicine: A Brief Review
- Overall Description of the Human Body
- Physical, Chemical, and Rheological Properties of Blood
- Modeling the Body as Compartments, Sources, and Streams
- Transport through Cell Membranes
- Artificial Kidney Devices
- Artificial Heart-Lung Devices

■ *Part II: Biochemical Engineering*

- Review of Microbiology and Chemicals of Life
- Kinetics of Enzyme-Catalyzed Reactions
- Kinetics of Key Rate Processes in Cell Cultures
- Design and Analysis of Biological Reactors
- Transport Phenomena in Bioprocess Systems

TABLE 2
Course Content: "Process Control"

- Incentives for chemical process control, design aspects, and control hardware
- Analysis of the dynamic behavior of chemical processes
 - Fundamental models, input-output models, state space models
 - Linearization of nonlinear systems
 - Laplace transforms, transfer functions
 - Dynamic behavior of first- and higher-order systems
 - Time delay, inverse response
 - Empirical models from plant data
- Analysis and design of feedback control systems
 - Feedback control (PID control, time-domain criteria, internal-model control)
 - Stability analysis, root locus analysis
 - Frequency response techniques, Bode diagrams
 - Performance of feedback control
- Enhancements of single-loop control (cascade, feedforward, inferential control)
- Model predictive control
- Multivariable processes: interaction, multi-loop control, multivariable control
- Process control design

TABLE 3
Summary of Student Profiles and Project Descriptions
 (UG-Undergraduate: G-Graduate)

Students (Their backgrounds, special interests, specifications, etc.)	Project ID	Courses			Project ID	Project Topic	# Students
		ChE IB	ChE PC Taking Taken				
UG Biology	1	✓			1	Comprehensive review of glucose-insulin interactions	1
UG ChE	2	✓		✓	ChE 2	Effect of food on glucose insulin interactions	2
UG ChE	2 and A	✓	✓		IB 3	Glucose insulin interactions in a healthy man	3
UG ChE, Biomedical Program	3 and A	✓	✓		4	Effect of exercise on glucose insulin interactions	2
UG ChE, Biomedical Program	3	✓		✓	5	Studying metabolic pathways of liver	1
UG ChE	3	✓		✓			
UG ChE, Biomedical Program	4	✓		✓			
UG ChE	4 and B	✓	✓		ChE A	Modeling pancreas of a healthy man	2
G ChE, Interest in Transport Phe.	B		✓		PC B	Modeling metabolic pathways of liver to control glucose level in blood	3
G ChE, Interest in Biotechnology	5 and B	✓	✓		C	Effect of daily activities on dosage of insulin	2
UG ChE, Attended Medical School	C		✓		D	Optimal timing and dosage of insulin	1
UG ChE	C		✓				
UG ChE	D		✓				

neering students and one-fourth of the process control students volunteered to work on this project.

PROJECT DESCRIPTION

The purpose of this project was to analyze the dynamic behavior of glucose-insulin interaction in a healthy person and/or in a diabetic patient. A pharmacokinetic model of diabetes mellitus originally developed by Puckett^[1] had been used previously, and an MS student who was working on this project at IIT wrote Matlab codes for it.^[2] These codes were given to the students so they could spend their time and energy in understanding the fundamental phenomena involved in the glucose-insulin interaction rather than writing and debugging code. A summary of the student profiles in both courses performing a project, along with the project topic, is given in Table 3. Students were grouped by taking into account their backgrounds and the status of their course registrations. In the IB course we tried to match students so that at least one of them was concurrently taking, or had already taken, the PC course. In the process control course, we rearranged them so that if all the group members were taking both

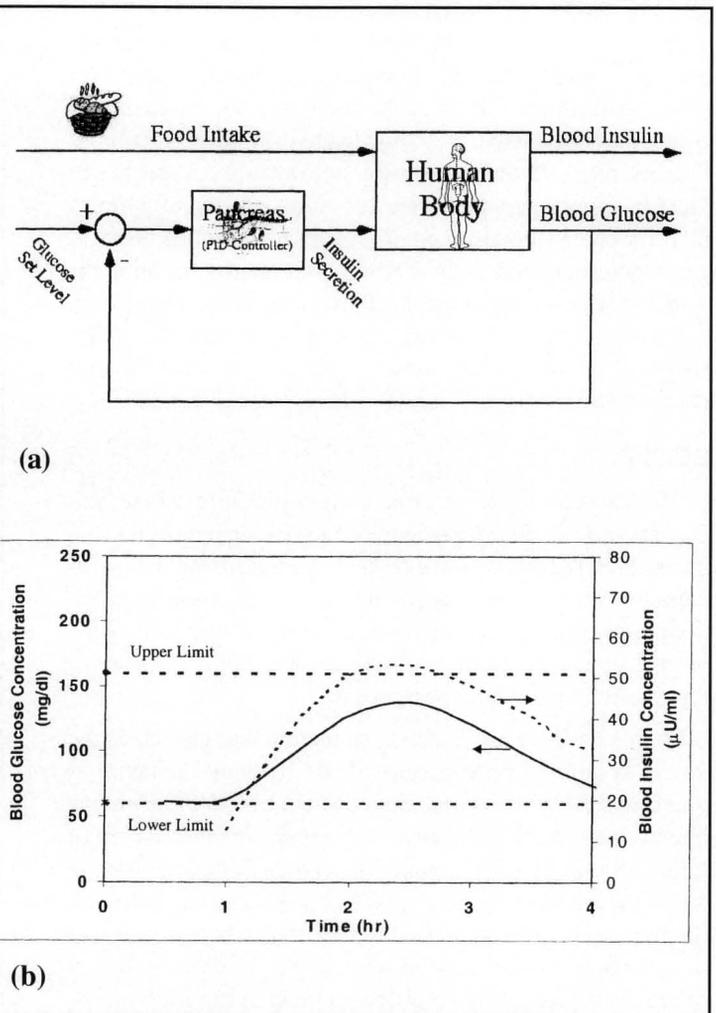


Figure 1.

- (a) Block diagram representing the pancreas as a PID controller and the human body as a multi-input-output process;
- (b) The effect of food intake on blood glucose and insulin regulated by pancreas.

courses they switched members to ensure that no student did exactly the same project in both courses.

Introduction to Bioengineering

The projects were assigned after the instructor covered the topics in the course, and the students were allowed five weeks to work on the projects. At the end of this period, students presented their findings in a ten-minute presentation session as a final project, worth 20% of their

course grade.

A variety of students from different backgrounds participated: there was one graduate student with biotechnology as his area of interest, seven chemical engineering undergraduate students, and one biology undergraduate student. There were also four graduate students auditing the course who did not prepare a project but participated in the work by giving feedback during the presentations. Four of the undergraduate students were registered in the Biomedical Engineering Program and were going to continue their education in medicine. The biology student was registered in the Biotechnology Certificate Program. A suggested timeline for these projects was

- Literature review (1 week): Students were given a brief description for each of the projects and were asked to make a literature survey to provide background material on the specific topic of interest.
- Mathematical Model (1 week): A mathematical model in Matlab code was provided and the students were expected to spend a week on understanding the code and using it efficiently under the supervision of both the instructor and the graduate student who wrote the code.
- Modification of the Model (1 week): Depending on the project description, some modifications in the Matlab code were needed. Students made such changes to the original code.
- Testing and Validating the Results (1 week): The numerical results after the necessary modifications have been produced and validated against the available literature data.^[1,3,4]
- Preparing the Report (1 week): Students were given a week to write their detailed final reports and to prepare their oral presentations. This enhanced their ability to support their work and ideas and provided immediate feedback on what the students learned from this experience.

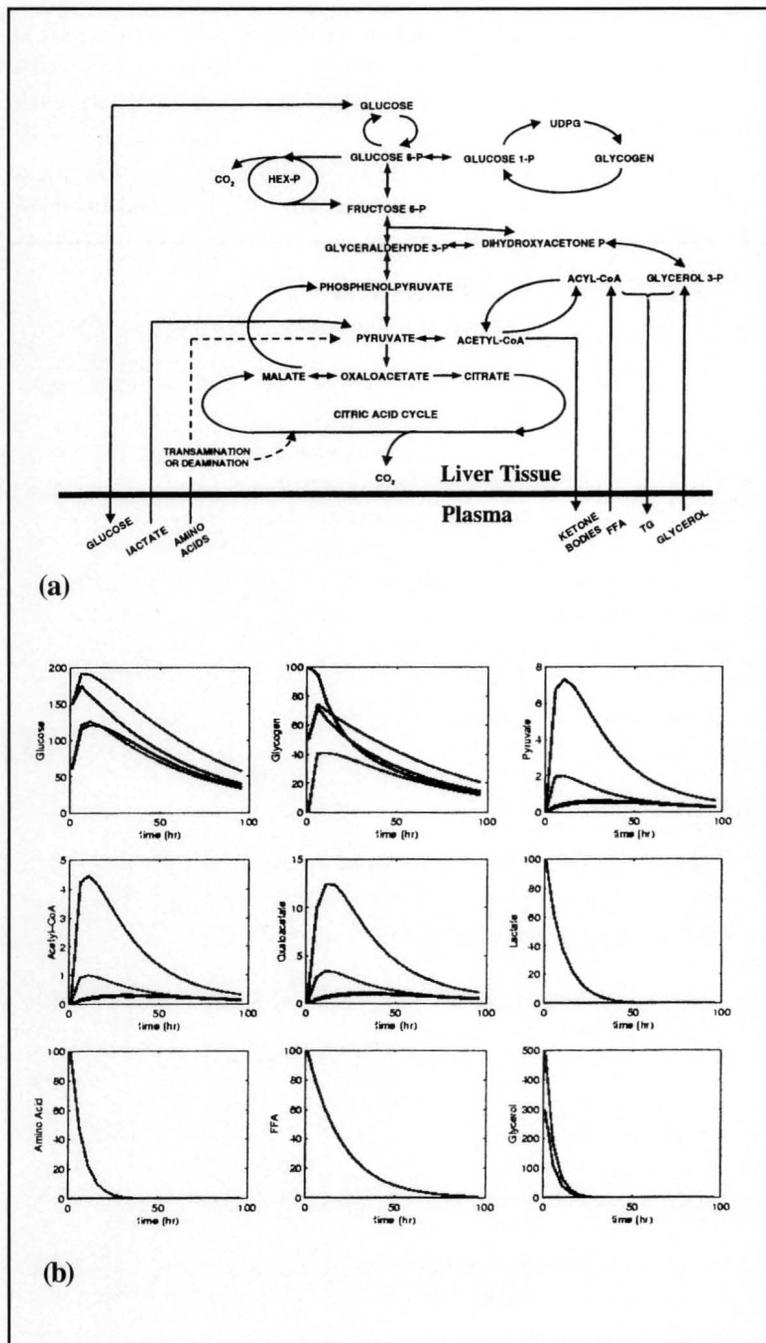


Figure 2. (a) A simplified metabolic pathway network of the liver; (b) Concentration profiles of intermediate metabolites for several sample runs.

The student from the Biology Department carried out a comprehensive review on glucose-insulin interactions in the human body, with an emphasis on the interactions in different organs. The three Biomedical Program students concentrated on glucose-insulin interactions in a healthy person and tried to understand the underlying mechanisms (see Figure 1). The graduate student put her efforts into studying the metabolic pathways of the liver using metabolic engineering concepts, initiating a promising research topic^[5] (see Figure 2). Other students worked on

investigating the effects of exercise or food intake on glucose-insulin interactions in a diabetic patient (see Figure 3).

Process Control

In the process control course, students were asked to work for two weeks on the project and to report their findings through project reports and presentations. This would account for two homework assignments and 4% of their overall grade. The description of a suggested project on the control of glucose level in blood was

In healthy people, the pancreas controls the glucose level in blood. When the pancreas does not function properly, the person is diagnosed as a diabetic patient, and his blood glucose level is controlled by insulin injections. Such a patient has to be careful about his diet as well as his exercise.

Investigate different cases on a model human body: a healthy person, a patient under nominal conditions, the food intake of a patient, and the exercise of a patient.

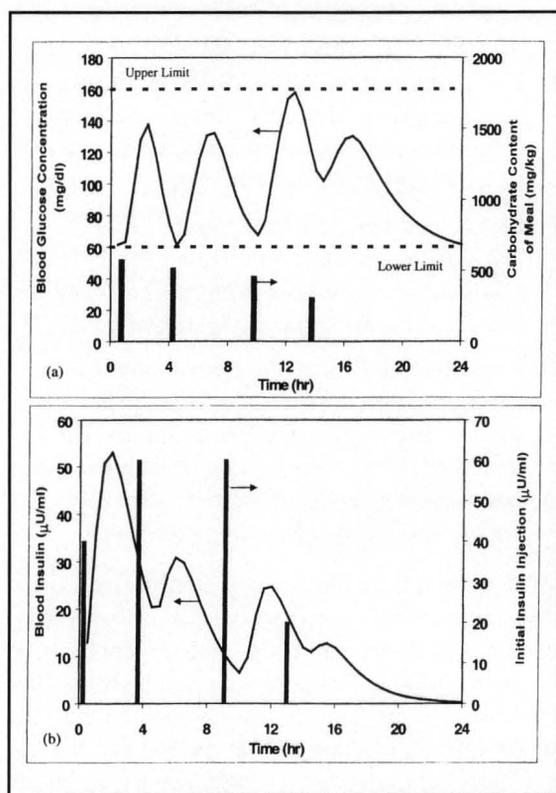


Figure 3. A typical blood glucose and insulin concentration profile for repetitive intake of food.

Test closed-loop and open-loop controllers on the model equations. Involve tasks such as finding the parameter subspace where the system works in a healthy regime, determine the appropriate dosage of insulin injection for a patient, and find the food and exercise tolerance limits for a patient.

The other project titles in the PC course were “Search for a Power Law,” “Internal Model Control,” “Complex Systems,” and “Population Dynamics.”

Student groups were told to select one of these topics or to come up with their own project proposals. More than one group was allowed to select one title, but all groups were expected to work separately and to pursue different tasks.

Students in the IB course were invited to select the “Control of Glucose Level in Blood” project. Apart from the four students in IB,

TABLE 4
Project Questionnaire

	<i>Low - High</i>
1. What was your level of competence using Matlab before the project?	1 2 3 4 5
2. What is your level of competence using Matlab after the project?	1 2 3 4 5
3. What is the difficulty level of this project compared to other course projects?	1 2 3 4 5
4. What is the relevance of your project title to your area of interest?	1 2 3 4 5
5. How would you rate the challenge of the project?	1 2 3 4 5
6. Overall, how would you rate this project?	1 2 3 4 5
7. How many hours did you spend on this project?	
8. Are you taking Introduction to Bioengineering	No Yes
Are you taking Process Control	No Yes
9. Facilities/tools at IIT were okay.	1 2 3 4 5
10. If I had more time, I would prepare a better project.	1 2 3 4 5
<i>I received help dealing with the project from the instructor and TAs...</i>	
11. ...as exchange of ideas	1 2 3 4 5
12. ...as exchange of knowledge	1 2 3 4 5
13. ...as technical support	1 2 3 4 5
<i>I received help dealing with the project from my friends...</i>	
14. ...as exchange of ideas	1 2 3 4 5
15. ...as exchange of knowledge	1 2 3 4 5
16. ...as technical support	1 2 3 4 5
17. This project was a useful learning tool for me.	1 2 3 4 5
18. It is easily applicable to other areas.	1 2 3 4 5
19. The goals were reasonable	1 2 3 4 5
20. I used my knowledge from other courses	1 2 3 4 5
21. I would consider engaging further research in this field	1 2 3 4 5

four more students picked this topic, signifying the appeal of biomedical topics among the students. They formed a valuable "control group" similar to IB students involved in the project who were not taking PC, which gave us the opportunity to monitor cross-course interactions.

Student interest in this topic was also evidenced by the contribution of other class members during project presentations. Two of the eight students performing a project on this topic were graduate students with interests in biotechnology and transport phenomena. One of the undergraduate students had previously attended medical school and provided valuable perspective on the subjects.

Some of the PC students were assigned the task of devising a control mechanism centered on different organs, such as the pancreas and the liver, as well as investigating the timing and dosage effects of insulin injections. Other students considered projects on topics other than the glucose-insulin interaction.

After the oral presentations in both classes, students were given a questionnaire to provide feedback to the instructors. They were carefully informed that the questionnaire (see Table 4) would be used only for course enhancement and educational research purposes and that it would not have any effect on grading.

Evaluation of the returned questionnaires indicated that all students showed improvement by at least one level in their competence in Matlab, accounting for an average increase of 70%. Although they find this project difficult (4.15 out of 5.00) and challenging (4.40) with respect to other class projects, they found it quite relevant to their own area of interest (3.50) and were willing to engage in further research in the field (3.47). Most of them reported that they needed more time to deliver a better project (4.20), which is an indication of their interest and willingness to be involved in it.

The students tended to receive help from instructors and TAs (3.60) rather than their peers (2.50). They found it a useful learning tool (3.75) with quite reasonable goals (3.45), although they were near-neutral to the applicability in other areas (3.35).

Overall, the students rated the project an average of 3.90. The fact that they have used their knowledge from other classes (3.70) suggests that the initiation of a cross-course platform may become a very useful learning tool, supporting our hypothesis.

CONCLUSIONS AND FUTURE DIRECTIONS

Diversity of interests, technical abilities, and states of knowledge among students provided unique feedback for

... The project played an important role in triggering the scientific curiosities of the students and providing an opportunity to adapt their knowledge to different fields.

future improvements in this cross-course project assignment. The choice of the project topic turned out to be an attractive one due to the popularity of biomedical engineering in education and research. The project played an important role in triggering the scientific curiosities of the students and providing an opportunity to adapt their knowledge to different fields. As a follow-up, we developed additional educational software in order to help students to explore many case studies.

The cross-course project approach to teaching bioengineering and process control described in this paper directly benefited four students taking both courses concurrently. The other four who had taken the process control class in the previous semester found that the project helped them integrate their acquired

knowledge in process control to a bioengineering project. Hence, eight out of nine bioengineering students were served by this cross-course initiative. As a result of this experience, we are looking forward to offering such a cross-course platform in future courses.

ACKNOWLEDGMENTS

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DEVELOPING THE BEST CORRELATION FOR ESTIMATING THE TRANSFER OF OXYGEN FROM AIR TO WATER

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The study of engineering is usually carried out in a defined sequence. Students are first taught a set of basic tools that includes, for example, mathematical concepts and solution procedures along with the various conservation laws. They then apply these concepts to elementary problems associated with their chosen discipline. In the final stages of the educational process, the simple concepts are extended to allow the students to apply them to multifaceted engineering problems.

Due to the complexity of systems of practical interest, theory developed around simple systems cannot normally be applied in the form derived. Often the theory is used to identify the set of governing variables, and a relationship between these variables is then established empirically. To generalize these solutions over a number of experimental conditions, variables are often gathered into dimensionless groups. Although the number of independent dimensionless groups is governed by Buckingham's "Pi" theorem,^[1] a number of useful groups have already been defined. These dimensionless groups represent ratios of competing effects, expressed in terms of experimental variables. Thus, development of an empirical relationship depends somewhat on the experience of the engineer or researcher. If particular effects are not identified as being important in the primary analysis, then they cannot be reflected in the final solution.

It is imperative that students be taught the following regarding problem analysis:

- ▶ *There are many different design equations that can be developed, depending on what assumptions are made. These assumptions are choices and are left to the judgment of the process engineer.*
- ▶ *The engineer should always use the applicable set of data to formulate a process design.*

- ▶ *More than one approach to a given problem may lead to a reasonable answer. The best approach is to consider many different methods of achieving a solution, but emphasis should be placed on the solution achieved by using the set of data most applicable to the problem at hand.*
- ▶ *It is often not possible to verify the results of an estimated parameter since a practical and accurate alternative measurement method may not exist. Thus, one may have to accept the results of an empirical correlation.*

We developed, and describe here, a laboratory exercise in an attempt to convey some of the above messages. It is based on the experimental determination of the overall mass-transfer coefficient describing the transfer of oxygen to water in an agitated tank.

OBJECTIVES OF THE LABORATORY

The objectives of the laboratory exercise were to

- *Analyze a problem involving the transfer of oxygen to water and formulate a set of mathematical equations to adequately describe the process*
- *Fit the developed equations to experimental data to deter-*



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On a practical level, the lab deals with benign materials. As such, there are no fume hood requirements or disposal problems. The lab can easily be extended to examine the effect of other variables, such as temperature, oxygen partial pressure, and liquid volume.

mine the mass-transfer coefficient

- Study the influence of the measuring device on estimates of the mass-transfer coefficient
- Develop the semi-empirical equations first put forth by Richards to estimate the mass-transfer coefficient
- Compare experimental results with estimates obtained from the Richards equation
- "Tailor" the Richards relation so that it makes the most use of the data collected

EQUATION DEVELOPMENT

Mass Transfer Coefficient from Experimental Data

The transfer of oxygen from a gas to a liquid phase can be divided into a number of transfer resistances.^[2] The set of equations that describes the transfer of oxygen from a gas phase to water in a batch system is dependent on the assumptions applied. Some of the issues to be considered are:

- The change in concentration of oxygen in the air over the residence time in the liquid phase
- The transfer of inert components from the air, in addition to oxygen
- The composition of the particular gases used
- The change in gas holdup with time
- The mixing characteristics of the gas phase
- The mixing characteristics of the liquid phase
- The presence of additives in the liquid phase
- The change in volumetric gas flow rate due to the transfer of matter from the gas to liquid phases
- The resistance to mass transfer across the gas-liquid interface
- The influence of surface aeration

The implications of various assumptions on the resulting differential equations are discussed elsewhere.^[3-9] For the current experimental setup, the following assumptions are assumed reasonable:

- There is negligible change in oxygen concentration in the gas phase.
- The gas holdup stays constant with time.
- The concentrations of oxygen in the gas and liquid phases are in equilibrium at the gas-liquid interface.
- The liquid is well mixed.

These assumptions lead to the following equations for the gas and liquid phases:

$$\frac{dC_L}{dt} = K_L a (C_L^* - C_L) \quad (1)$$

$$\frac{dC_G}{dt} = 0 \quad (2)$$

where $K_L a$ is the volumetric mass-transfer coefficient.

These equations can be integrated subject to the initial conditions $C_L(0) = 0$ and $C_G(0) = C_G^0$ to yield

$$C_L(t) = C_L^* (1 - e^{-K_L a t}) \quad (3)$$

$$C_G(t) = C_G^0 \quad (4)$$

The problem is further complicated when the measurement method is considered in the analysis. One of the most common and convenient methods for measuring dissolved oxygen is through application of a dissolved oxygen electrode. To make a measurement, oxygen dissolved in the surrounding fluid must diffuse to the probe membrane, across the membrane, and finally through the probe solution to the active electrode tip. A number of approaches have been applied successfully to model this process, such as Fick's second law.^[9] However, if the bulk solution in the tank is not viscous, transport through the electrode membrane can be treated as a first-order process, described by an equation of the form

$$\frac{dC_p}{dt} = \frac{1}{\tau_p} (C_L - C_p) \quad (5)$$

Here, the diffusion through the probe solution is neglected. Substituting Eq. (3) into Eq. (5) and integrating the result subject to the initial condition

$$C_p(0) = 0 \quad (6)$$

an expression relating the overall mass-transfer coefficient to the probe output can be derived

$$C_p(t) = C_L^* \left(1 + \frac{K_L a}{k_p - K_L a} e^{-k_p t} - \frac{k_p}{k_p - K_L a} e^{-K_L a t} \right) \quad (7)$$

Using this equation, the overall liquid mass-transfer coefficient can be determined directly from the probe output. To determine the probe time constant, Eq. (5) is solved, subject to the conditions given by Eq. (6) and Eq. (8):

$$C_L(t) = C_L^* \quad (8)$$

In Eq. (8), C_L^* is a constant for a given oxygen partial

pressure and system temperature. Using Eqs. (6) and (8), Eq (5) can be integrated to yield

$$C_p(t) = C_L^* (1 - e^{-k_p t}) \quad (9)$$

Generalized Correlation of Oxygen-Transfer Data

The volumetric mass-transfer coefficient, $K_L a$ is a complex function, dependent on the system geometry, the properties of the liquid, and the process operating conditions. In terms of basic variables, the function can be expressed as

$$K_L a = K_L a(d_i, n_i, h_i, w_i, l_i, d_T, h_L, n_B, w_B, \rho_f, \mu_f, \sigma_f, D_{O_2}, N, v_S, v_t, g) \quad (10)$$

In developing his correlation, Richards considered K_L and "a" separately. For geometrically similar vessels, dimensionless groups related to geometry do not vary. In this particular situation, the overall mass-transfer coefficient per unit transfer area, K_L , associated with the transfer of oxygen from a gas phase to a Newtonian fluid is expected to be a function of the variables

$$K_L = \text{fn}(N, d_i, \rho_f, \mu_f, D_{O_2}) \quad (11)$$

From Buckingham's Pi theorem, three dimensionless groups can be created. Thus, as suggested by Rushton,^[10] the relationship can be written

$$\frac{K_L d}{D_{O_2}} = K_1 \left(\frac{N d_i^2 \rho_f}{\mu_f} \right)^\alpha \left(\frac{\mu_f}{D_{O_2} \rho_f} \right)^\beta \quad (12)$$

Here, K_1 is a constant that accounts for the geometry of the particular system. For convective mass transfer between spherical particles and a liquid, α has been shown empirically to have a value in the range of $0.4 \leq \alpha \leq 0.6$.^[11] In his derivation, Richards used a value of $\alpha = 0.5$. Thus, for constant diffusivity and fluid properties, and assuming that the gas consists of spherical bubbles, Eq. (12) reduces to

$$K_L = K_2 N^{0.5} \quad (13)$$

Richards' development is completed by noting that the interfacial area for mass transfer is correlated adequately by Calderbank's equation^[11]

$$a = K_3 \left[\frac{(P_G / V_L)^{0.4} \rho_L}{\sigma_L} \right] \left[\frac{v_S}{v_t} \right]^{0.5} \quad (14)$$

As shown through the dimensional analysis performed by Rushton, *et al.*, P_G is itself a function of a subset of the variables introduced in Eq. (10).^[12] For the assumption of constant fluid properties applied above, the Richards correlation for the overall mass transfer coefficient is obtained by multiplying Eqs. (13) and (14) to yield

$$K_L a = K_4 (P_G / V_L)^{0.4} v_S^{0.5} N^{0.5} \quad (15)$$

Data from a number of different systems have been correlated

using the relation developed by Richards.^[13,14]

In applying the Richards equation, data on the power requirements of the gassed system are not always readily available. Therefore, as part of the current development, it is useful to express the correlation in terms of the more commonly measured variables as they appear in Eq. (10). Useful for this purpose is the empirical correlation put forth by Michel, *et al.*,^[15]

$$P_G = K_5 \left(\frac{P^2 N d_i^3}{Q^{0.56}} \right)^{0.45} \quad (16)$$

Note that this equation is not dimensionless, and thus care should be taken when extrapolating outside the range in which the data was collected. An estimate of the *ungassed* power requirements can be obtained from the dimensionless relationship based on the Rushton's power number.^[12] For geometrically similar vessels, function is of the form

$$Po = \frac{P}{N^3 d_i^5 \rho_f} = K_6 \left(\frac{d_i^2 N \rho_f}{\mu_f} \right)^\gamma \left(\frac{d_i N^2}{g} \right)^\lambda = \text{fn}(\text{Re}, \text{Fr}) \quad (17)$$

The Froude number (Fr) is only important if a vortex is formed. As most systems are baffled, the dependence of the power number (Po) on Fr is usually not considered, and Eq. (17) reduces to a function of Re only. This function is often expressed graphically. Since the dimensionless groups

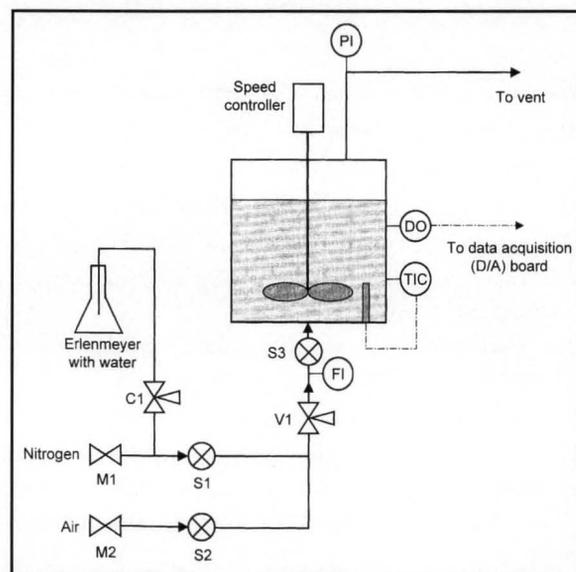


Figure 1. Experimental apparatus. Temperature (TI), pressure (PI), gas flow rate (FI), and dissolved oxygen (DO), were measured continuously. Only the signal from the dissolved oxygen probe was sampled by the data acquisition board, however. Solenoid valves S1, S2, and S3 were used to choose the source of the gas added to the fermenter, while valve V1 was used to adjust the flow rate. Valve C1 was used to purge the Erlenmeyer flask with nitrogen for determination of the probe time constant. Details of the procedure can be found in the text.

related to geometry have not been included, however, a single curve for each impeller configuration is required. Thus, using Eqs. (15) through (17), an estimate of the mass-transfer coefficient can be obtained.

EXPERIMENTAL

Apparatus

A 4-L tank was used for all experiments (see Figure 1). The vessel was 13 cm in diameter and had a height of 30 cm. No baffles were installed. All experiments were performed using 2 L of distilled water, resulting in a liquid depth of approximately 15 cm. A flat-blade propeller was used that was 6.5 cm in diameter from tip to tip. The propeller had 4 blades and was located 2 cm from the bottom of the vessel. Air was introduced into the bottom of the tank through a sparger that consisted of four equally spaced holes, directed radially outward. The temperature was controlled by means of a 300-W heater connected to a controller (Omega Model BS5001J1). Dissolved oxygen was measured using a dissolved oxygen electrode (Ingold DL-531) in conjunction with a digital meter equipped with an analog output (Cole-Parmer Model 01971-00). Data from the meter was logged on a personal computer by means of a data-acquisition board and bundled data-acquisition software (LABTECH notebook for Windows).

Experiments were run over a range of gas flowrates (2-4 L min⁻¹) and stirring speeds (100-1200 rev min⁻¹). Prior to each set of experiments, the probe was calibrated using nitrogen and oxygen saturated solutions of water. All experiments were performed at 30°C and at atmospheric pressure.

Determination of Probe Time Constant

The dissolved oxygen probe was placed into a flask of

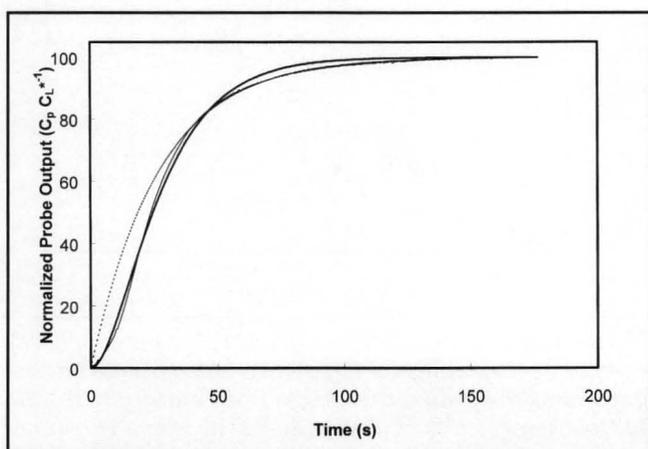


Figure 2. Fit of Eq. (3) (dotted line) and Eq. (7) (thick solid line) to experimental data (thin solid line). Experimental data were generated at an air flowrate of 3 L min⁻¹ and a stirring speed of 1100 rev min⁻¹. In calculating $K_L a$ by Eq. (3), only data between 30 and 98% saturation were considered, as described in the text.

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water that had been purged to saturation with nitrogen (see Figure 1). After a reading of 0% had been established, the probe was quickly immersed into the vessel containing 2 L of water saturated with oxygen to 100%. Under these conditions, the dynamics of the probe are described by Eqs. (5), (6), and (8). To facilitate the determination of the probe constant, a linearized form of Eq. (9)

$$\ln\left(\frac{C_L^*}{C_L^* - C_p}\right) = k_p t \quad (18)$$

was used. From Eq. (18), a plot of $\ln\left(C_L^* / (C_L^* - C_p)\right)$ versus t should yield a straight line with a slope of k_p . The slope of the best-fit line was determined by linear regression.

Determination of $K_L a$

The vessel was first purged with nitrogen until the dissolved oxygen probe stabilized at a value of 0%. The purge gas was then switched instantaneously to air through means of a series of solenoid valves (see Figure 1). An estimate of the mass-transfer coefficient was then obtained by fitting Eq. (7) to the data collected. As the model function cannot be linearized, a nonlinear regression algorithm was used to extract the best estimate of $K_L a$ from each data set.

RESULTS AND DISCUSSION

As a preliminary exercise to the laboratory, students were asked to develop the appropriate equations with which to estimate $K_L a$. It became apparent to the students during this exercise that the set of equations generated depends on the assumptions that were made with respect to specific aspects of the problem. For instance, if it was assumed that the rate of mass transfer from the gas to liquid is small compared to the dynamic associated with the probe, then $(1 / K_L a) \gg \tau_p$, and the effect of the probe is negligible. Under these circumstances, the rate of mass transfer can be calculated adequately from Eq. (3); but if this is not the case, then the probe dynamics must be taken into account.^[16] Thus, a function such as Eq. (7) is required.

The probe constant was calculated by each group of students using a graphical approach. Typical values obtained for τ_p were between 14 and 17 s. From Eq. (5) the probe output should attain a value of 63% saturation when $t = \tau_p$. From the experimental data used to determine τ_p , this condition was verified (data not shown). Therefore, Eq. (5) proved to be an adequate representation of the dynamics of the probe.

Typical data obtained by the students for calculation of $K_L a$ is shown in Figure 2. It has been shown that truncating data collected early in the experiment can minimize the effect of the probe on the estimate of $K_L a$.^[17] Therefore, under appropriate conditions, reasonable estimates of $K_L a$ can be obtained from Eq. (3) and knowledge of the probe dynamics is not required. Even when these conditions are

met, however, due to the exponential nature of Eq. (3) the best estimates of $K_L a$ are obtained from Eq. (3) using data collected at times on the order of the time constant, $\tau=1/K_L a$. As such, it is recommended that data above 30% saturation never be discarded.^[17]

For the current exercise, when neglecting the effect of the probe, only data between 30 and 98% saturation were considered when determining $K_L a$ using Eq. (3). When the probe dynamics were considered, however, Eq. (7) was applied and all of the data collected were used. Using the data shown in Figure 2, Eq. (3) and Eq. (7) yield $K_L a$ estimates of 134 h^{-1} and 285 h^{-1} , respectively. Therefore, serious errors result if the probe dynamics are not considered. This is to be expected since the dynamics of the mass-transfer process and the probe are on the same order for these data. Thus, the concept that the measuring device is an integral part of a process is reinforced.

From Figure 2 it is apparent that Eq. (7) adequately represents the data, where Eq. (3) does not. In addition, for two first-order processes in series, the sum of the time constants of each process should equal the time at which the overall process achieves a value of 63%. For the data presented, a value of 63% is achieved at approximately 30 s. The sum of the time constants, $\tau_p + 1/K_L a$, is equal to 29 s. Therefore, the assumptions that led to the development of Eq. (7) appear to be appropriate—other formulations could also fit the data as well or possibly even better, however. For instance, unsteady-state diffusion to the active element in the probe could have been solved using the appropriate form of the diffusion equation.^[17] The solution to this problem can then be fit to the data to determine the probe time constant.

The range over which the dynamics of the probe can be neglected was studied by comparing estimates of $K_L a$ obtained using Eqs. (3) and (7) (see Figure 3). From this figure, it can be seen that the two estimates deviate at relatively low values of $K_L a$. Quantitatively, it is apparent that the impact of the probe becomes important when the probe time constant is 20% of the time constant associated with the transfer process, $1/K_L a$. This “rule of thumb” has also been suggested by others.^[17]

The data generated by the students was then compared with the Richards equation. This was accomplished by plotting the $K_L a$ estimates obtained by the students on the same axes as the data used to generate the relationship in the original work by Richards (see Figure 4). When originally presented, $K_L a$ was quoted in units of $\text{mML}^{-1}\text{h}^{-1}\text{atm}^{-1}$.^[13] This selection of units was most probably related to the sodium sulphite oxidation method that was used to generate the data. Data generated using this technique are often displayed as $H'K_L a$, where H' is Henry's constant.^[18] To facilitate comparison with the data generated by the students, data used to generate the original correlation were divided by Henry's constant at 30°C (see Figure 4). In the laboratory exercise,

axes complete with the data used by Richards were handed out in printed form to each lab group. Thus, the comparison exercise necessitated that the points be plotted by hand. Therefore, the students were forced to critically examine the deviation of the experimental values from the Richards equation. The data generated scatters within the bounds of the original data sets. This scatter is rather large, however. For instance, $K_L a$ values of between 75 and 250 h^{-1} correspond to a value of 300 on the abscissa. Thus, estimates by the corre-

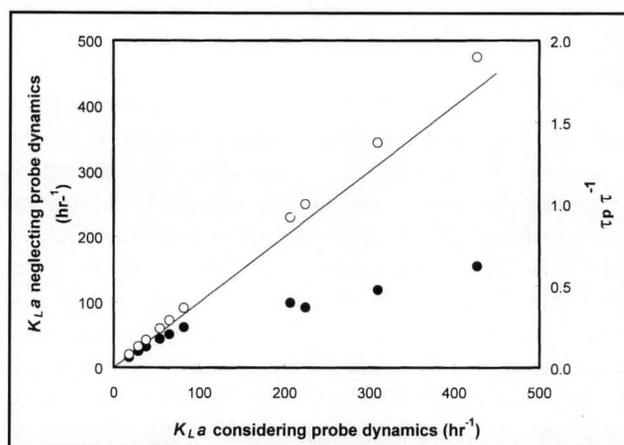


Figure 3. Comparison of estimates of $K_L a$ obtained by considering (Eq. 7) and neglecting (Eq. 3) the probe dynamics. Closed circles represent the $K_L a$ estimates, while open circles represent the ratio of the probe time constant to the time constant of the transfer process, where $\tau=1/K_L a$. The solid line indicates a perfect correspondence between the two estimates of $K_L a$.

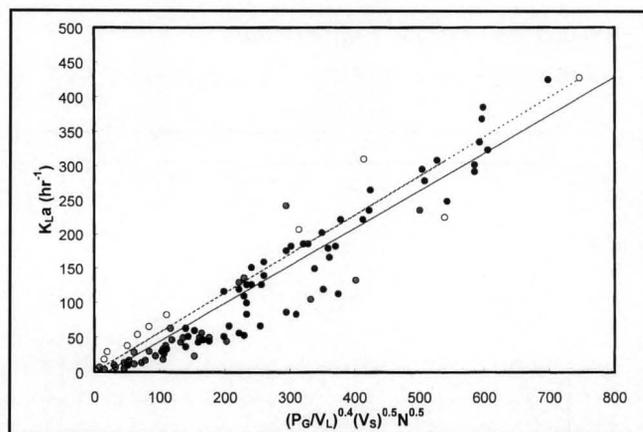


Figure 4. Assessment of the applicability of the Richards equation to experimental apparatus. The ordinate has the units indicated, while the abscissa has units of $(\text{HP}/1000 \text{ L})^{0.4}(\text{cm}/\text{min})^{0.5}(\text{RPM})^{0.5}$. Black (Richards^[13]) and gray (Cooper^[18]) circles represent the data originally used by Richards to assess his correlation. Results were divided by Henry's constant at 30°C , as described in the text. The solid line represents the best fit to these data, as suggested by Richards. Open circles represent data generated as part of the current laboratory exercise. The dotted line represents the results of Eq. (19).

lation are on the order of $\pm 50\%$. This finding is often difficult for many students to accept, as critical analysis of empirical correlations on this level is new for them.

The correlation developed by Richards underestimates the data generated by the students in almost all of the cases (Figure 4). There are two plausible explanations for this result. First, the original development of the correlation was meant to apply to geometrically similar vessels.^[13] Therefore, it is possible that the consistent offset from the Richards correlation is related to geometric differences between the systems used to generate the various data sets.

The Richards equation can be tuned for a specific geometry as follows: For the experimental system at hand, only N and Q are varied; furthermore, for Reynolds numbers associated with all stirring speeds, it can be shown that Po is constant in Eq. (17).^[14] Thus, Eqs. (15) through (17) can be reduced to

$$K_L a = K_7 N^{1.76} Q^{0.4} \quad (19)$$

This equation has one adjustable parameter (K_7) that accounts for geometry and the fluid properties of the system. As a first step to improving the correlation, K_7 was determined using only the student data. The resulting equation was plotted on Figure 4. Because only data specific to the system under study was used, Eq. (19) is a better representation of the system used in the study, as is evident in the superior fit.

A second plausible explanation to account for the differences noted between the Richards correlation and the experimental data is related to surface effects. In its development, the Richards correlation assumes that the tanks are well

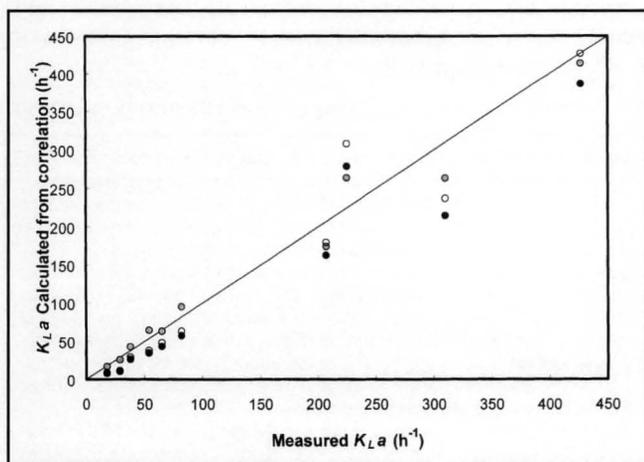


Figure 5. Ability of various correlation equations to fit the experimental data. Black circles represent results of the Richards correlation as originally presented (Eq. 15). Open circles represent the Richards correlation tailored for the geometry of the experimental system (Eq. 19). Grey circles represent the equation resulting when surface effects are considered through inclusion of the Froude number (Eq. 22).

baffled.^[13] As a result, surface effects are negligible and no dependence on the Froude number is expected. The Froude number was also not considered in application of Eq. (17) for the same reason. The experimental apparatus used by the students had no baffles. Thus, a dependence of the $K_L a$ on the Froude number is expected, especially for larger values of N .

To address this shortcoming in the original derivation, the Richards correlation is further modified to account for possible surface effects. The Froude number is defined as

$$Fr = \left(\frac{d_i N^2}{g} \right) \quad (20)$$

The desired equation can be obtained from Eqs. (19) and (20), and has the general form of

$$K_L a = K_7 \left(\frac{d_i}{g} \right)^\lambda N^{2\lambda+1.76} Q^{0.4} \quad (21)$$

Although the value of λ is not known, it is recognized that Eq. (21) is also a function of N and Q only. The specific value of λ could be determined through regression using the experimental data collected. In the resulting equation, the exponent of N would be tailored to the data collected by the students, while the functionality of Q would be dictated by the data sets originally used by Richards. Therefore, a more reasonable approach is to tailor *all* exponents to the experimental data generated by the students. The result of this exercise is the equation

$$K_L a = K_8 N^{1.35} Q^{0.60} \quad (22)$$

The ability of this equation to capture the relevant features of the experiment is readily seen in Figure 5. While the Richards equation represents the data well, the best fit results when the equation is tailored to the experimental data collected. Thus, while an adjusted correlation coefficient, r^2 , of 0.81 is associated with the fit of Eq. (19), this value increases to 0.98 when Eq. (22) is applied. This result may seem obvious, as Eq. (22) has three adjustable parameters, while it appears as if Eq. (19) has only one. In actuality, however, both equations have three adjustable parameters. The difference is that the exponents in Eq. (19) were obtained from correlations fit using other sets of data, while those in Eq. (22) were fit to the data obtained with the current system only.

The difference among the three approaches becomes readily apparent at this point. As the equations are further tailored to the experimental data, the mathematical form better fits the data. Thus, the spectrum of possibilities associated with process design can be elucidated. When no data are available, the engineer must rely heavily on data generated from dimensionally similar systems. This approach is only justified, however, in the absence of reliable data associated with the system of interest. As data become available, the pre-

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A PROJECT-BASED SPIRAL CURRICULUM FOR INTRODUCTORY COURSES IN ChE

Part 3. Evaluation

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This series reports on the development, delivery, and assessment of a project-based spiral curriculum for the first sequence of courses in chemical engineering. The program represents significant restructuring of the introductory chemical engineering curriculum. Traditionally, a compartmentalized course sequence designed to build a conceptual foundation is taught during the sophomore and junior years, followed later by more integrated projects. Our new curriculum requires students to learn and apply chemical engineering principles by completing a series of open-ended design projects starting during their sophomore year. The new curriculum is spiral in that students' understanding of basic concepts is reinforced by revisiting them in different contexts with ever-increasing sophistication.

A more detailed explanation of the concepts, curriculum design, and implementation behind this effort was described in the first two part of this series.^[1,2] Part 1 described the curriculum design, and Part 2 detailed the implementation. In this paper we present the details of the assessment design, describe the results of our assessment, and draw conclusions about the success of the new curriculum.

BACKGROUND

The background describing the need for the new curriculum, the published research upon which it was based, and the philosophy behind our approach was presented in the first paper of this series.^[1] In this section we summarize the literature upon which our assessment plan was based.

An extensive array of literature exists regarding assessment of student learning. An excellent bibliography is available from the Department of Education^[3] and two good resources are available from the National Science Founda-

tion.^[4,5] There are also a number of references that outline the details of assessment plans aimed at continuous improvement.^[6-9] Most of the philosophy and techniques described in those articles are adaptable to individual educational research and curriculum reform efforts.

Assessment tools are generally categorized according to the types of methods and when they are applied during an educational project. There are two broad classes describing the timing of assessment. *Formative assessment* refers to periodic data collection and evaluation prior to project completion. It is used to improve the intervention during the project and helps answer the question, "Is it working?" *Summative assessment* concerns data collection and evaluation at project completion. It is used to make conclusions about project retention, alteration, or elimination and normally answers the question, "Did it work?"

There are two general classes of assessment types. Quanti-

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tative methods are those familiar to most engineers. They include exams (standardized, course exams, comprehensive, oral); surveys with statistical analysis (particularly pre/post); database analysis; written reports (laboratory, design, or research project); graded oral presentations; and graded portfolios. These methods are generally performance-based and measure what students can actually do. Within a discipline-specific context, it is relatively easy to evaluate student performance, but the design of the tool itself may be problematic. These methods can be used to evaluate both team and individual performance. Performance-based tools (authentic evaluation) were pioneered at Alverno College.^[10] O'Conner^[11] described a design-competition approach to performance assessment, and Miller, *et al.*,^[12] present a comprehensive assessment plan involving multiple types of evaluations.

Qualitative methods typically involve analysis of text and visual information. They include videotaping, audiotaping, direct observation, portfolios, self-reports, open-ended surveys, interviews, focus groups, performances, and journals. Engineers have been somewhat slow, however, in finding productive ways to adopt these methodologies that are used in developmental psychology and cognitive science. Most of the methods involve qualitative analysis that is unfamiliar to technologists. The main advantage of methods such as videotaping is that they record actual work—not student interpretations of what was asked of them in a survey. By observing students doing chemical engineering, we can probe how and why they learn. This can yield rich information about the learning process. Sometimes this information is quantified, but usually the results are qualitative.

Marcus^[13] summarized the main features of good and poor assessment plans. The keys to a good assessment plan are: use of both control groups and target groups to minimize variation, including control for contaminating elements; multiple measurements using multiple tools; a mix of formative, summative, quantitative, and qualitative tools; and use of an external evaluator. Good plans define measurable objectives and design the assessment methods directly from those objectives. They implement continuous feedback for improvement, use pre- and post-measurements, and include longitudinal studies when possible. The evaluation plan should uncover program flaws as well as attributes.

Poor assessment plans overemphasize one set of outcomes (for example, affective rather than cognitive) or one type of measurement (all quantitative); vaguely define the performance criteria; do not link data collection to the program;

rely on traditional tests for nontraditional interventions; and develop in-house instruments when validated ones are available.^[13]

Because any single assessment method has advantages and disadvantages, triangulation (the use of multiple measurements) is a key to valid assessment. Evaluation events that occur during and after the intervention are also important. When multiple measurements taken at different time points converge on common results, one can confidently draw conclusions about the observed process or outcomes.

METHODS

Our assessment plan was designed to probe student learning in basic chemical engineering and students' ability to demonstrate learning in both team and individual contexts. We also examined attitudes, satisfaction, and confidence about chemical engineering. For longitudinal data, we looked at individual student performance in follow-on courses in the junior and senior years. Our overall plan combined formative and summative measures and employed both qualitative (interviews, open-ended questionnaires, videotaping of student group work) and quantitative (pre/post surveys, standard course evaluation surveys, individual exams, and team problem-solving competitions) tools. External consultants were used extensively throughout the project.

Intervention and Comparison Cohorts

At the beginning of each implementation year we randomly selected a cohort of incoming sophomores to participate in the spiral curriculum. During the first implementation year, this was about one-third of the class. In the second implementation year, half of the incoming class was randomly selected. Selecting half in the second year meant we eliminated class size as a variable in our analysis. Students not selected were taught in the traditional fashion in a separate section and represented our comparison cohort. Each year we made minor adjustments (prior to the start of the academic year) to insure demographic similarity between the intervention and comparison groups. We also examined grades of each cohort in their first year at WPI. There were no significant differences in first-year performance between the two cohorts.

Since participation in the spiral curriculum was voluntary, students could withdraw at any time during the academic year and move into the comparison section. Only one student did that during the two years of implementation. No students were allowed to self-select into the experimental section. In the following discussion we will refer to the

The new curriculum is spiral in that students' understanding of basic concepts is reinforced by revisiting them in different contexts with ever-increasing sophistication.

intervention group as the *spiral-taught* cohort and the traditionally taught students (the control group) as the *comparison* cohort. Spiral-taught thus refers to all the components of the new curriculum, not simply just the spiral topic structure.

We did our best to control contaminating variables. Both cohorts were taught essentially the same material, using the same textbooks. Both cohorts met for the same number of class periods each week and, as schedules allowed, during the same class hour each day. When scheduling did not allow the latter, we avoided vastly different meeting times. For example, if the comparison group was scheduled at 11:00 a.m., we scheduled the spiral-taught section for close to that hour and avoided times such as 8:00 a.m. or 4:30 p.m.

Problem-Solving Competitions: Team and Individual

Team • At the end of each implementation year, we held a team-based problem-solving competition. All sophomores were invited to participate. Spiral-taught students were placed in teams and comparison students were placed in separate teams. Most students were teamed with others with whom they had not previously worked. We constructed teams with a mix of abilities (judged by grade records) and gender. All participants were paid, and the winning teams from each cohort were awarded additional prize money. This structure meant that from the student standpoint, they were competing only with peers (not comparison groups versus spiral groups). The participation rate was 75% for the first year and 90% in the second year.

Teams were given an open-ended chemical-process problem to solve and had two hours to develop their solution. The problem involved a simple reaction/separation process for the production of formaldehyde from the decomposition of methanol. Students were given the reaction and the desired production rate. They had to develop the process flowsheet, make reactor and material-balance calculations, and choose and design a separation scheme.

Each team selected one group member to present its solution. These ten-minute presentations were videotaped. The presentation videotapes and written student work were sent to three external experts in chemical engineering. Judges were given the problem solution, some guidelines for rating student work, and a form for reporting their analysis of each team's solution. The judges ranked all teams from best-to-worst on the basis of the technical work, not on the presentation quality. The highest ranked spiral team and the highest ranked comparison team were each awarded prize money. We were interested in the comparative rankings of spiral versus comparison teams. Judges were volunteers from academia and industry and had no knowledge of whether the teams were spiral-taught or comparison teams. We also videotaped each team during its two-hour working sessions to help us understand something about the process of solving chemical engineering problems.

Individual • At the end of the second implementation year we held an individual exam competition. Students were given an exam that tested four basic areas of chemical engineering. The exam was open-book and was designed at about Bloom levels 3-4: application and analysis. Again, all sophomores were invited and paid to participate. The participation rate was 61% of the total sophomore class. We offered the exam to juniors to probe long-term retention of basic knowledge. Only four participated, however, yielding too small a sample to draw conclusions. We blind-graded each individual exam using a numbering system that preserved student anonymity. To promote conscientious participation, we offered more cash to students scoring above 70% on the exam.

Questionnaires, Surveys, Interviews

We contracted developmental psychologists from the Frances L. Hiatt School of Psychology at Clark University for our external consultants. Kevin O'Connor and Lisa Comparini were the consultants, with Comparini being with us for most of the project. All questionnaires and surveys were designed by the consultants, and all interviews (in person or electronic) were conducted by Comparini. Both O'Connor and Comparini were intimately involved in the design of the competitions described above. Comparini conducted the analysis of the questionnaires and surveys.

RESULTS

The results from the major assessment measures are summarized below. In all cases, the results were positive regarding the success of the spiral curriculum project. Assessment design allowed us to probe program effects from a variety of different views. The converging results clearly demonstrate the superior educational benefits the new curriculum provided.

Team Problem-Solving Competition

Spiral-taught student teams were judged significantly higher than comparison teams in both years of the team competition.

In the first year, all three judges ranked the spiral teams as the top three of the six participating teams by a wide margin. In the second year, spiral-taught teams were unanimously ranked as the top two of eight total, and four of the top five teams were spiral-taught groups. This clearly demonstrates the ability of spiral-taught students to perform at higher levels than comparison students on open-ended problems.

In general, the judges' comments indicated that spiral-taught teams demonstrated better overall problem analysis than comparison teams. A more global, systems-oriented approach was taken by higher-ranked teams. Spiral-taught teams also showed more progress in generating a flowsheet, completing material balances, and handling equilibrium conversion calculations. Poorer team solutions (primarily comparison groups) were characterized by incomplete flowsheets,

trouble handling reaction products, and an inability to completely couple the reaction and separation portions of the process. Very often, comparison teams focused too much on one particular aspect and failed to demonstrate knowledge of the "big picture."

This performance assessment was a major milestone in our evaluation. Since one of our objectives was to improve students' abilities to solve open-ended problems in team situations, the results were very encouraging. Our evaluation plan was not designed to probe individual effects. For example, we did not run a section that had topic spiraling and no cooperative learning. We strongly believe, however, that repeated exposure to spiraled topics (a critical mechanism in improving knowledge retention) coupled with substantive team work is a major reason for the results.

Individual Exam Competition

Spiral-taught students performed better, as individuals, on basic chemical engineering problems.

We were not able to conduct this competition in the first implementation year, but we did conduct it at the end of the second implementation year. Twenty students participated, ten from each cohort. The results are summarized in Table 1 and Figure 1. As a group, the spiral-taught students showed better understanding of chemical engineering. The average score was higher for spiral-taught students and more of them scored above the 50% and 70% levels.

Figure 1 shows that spiral-taught students performed the same or better than comparison students in three of the four areas tested. Those four areas were material balances, classical thermodynamics, staged equilibrium separations, and so-

lution thermodynamics. A clear difference in learning material balances was shown. Spiral-taught students were continuously using this material in different contexts throughout the sophomore year. A similar difference, though not as dramatic, was seen for classical thermodynamics. It is significant that for the case of staged separations, the spiral-taught students had been exposed to the specific material tested (basic McCabe-Thiele calculations) several months prior to the exam. The comparison students were enrolled in the traditional course concerning this material at the time of the exam. Spiral-taught students did not do as well on the solution thermodynamics problem. This area was the most difficult to build into the spiral curriculum and we recognize that it is one area of the curriculum needing improvement.

A typical criticism of cooperative learning is that some students will be carried by their group. The individual exam results and the longitudinal data shown below serve to disprove that notion in our case. Again, the combination of topic spiraling, repeated exposure to open-ended problems, and extensive group work was successful in improving individual student learning.

Longitudinal Effects

Spiral-taught students received higher grades than comparison students in follow-on junior- and senior-level chemical engineering courses.

We tracked students throughout their academic programs to understand how participation in the new curriculum correlated with later performance. Examination of grades in our unit operations laboratory showed that teams comprised of two or more spiral-taught students generally received higher report and oral presentation grades than teams comprised

Cohort	Average Score	# Scores >50%	# Scores >70%
Spiral-Taught	21.7	5	3
Comparison	18.8	3	2

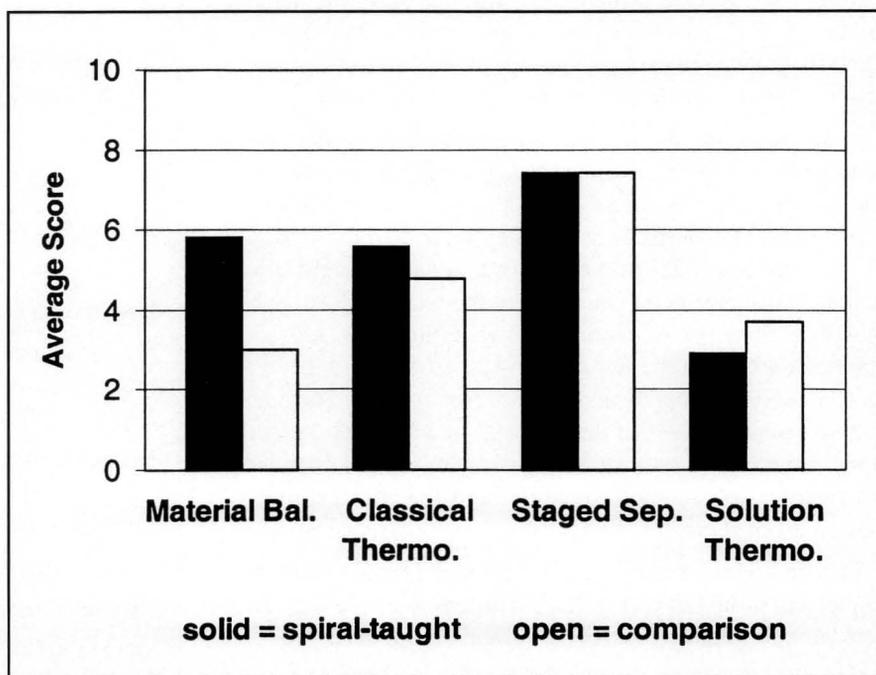


Figure 1.
Average score of each cohort on individual problems. Maximum score per problem was 10 points.

Examination of grades in our unit operations laboratory showed that teams comprised of two or more spiral-taught students generally received higher report and oral presentation grades than teams comprised mostly of comparison students.

mostly of comparison students.

WPI's upper-level program is heavily project-based. It makes sense that students experienced in project-based learning would show higher levels of performance in similar academic activities as they became juniors and seniors. These projects are similar to senior-level research (BS thesis) projects done at other schools. The first cohort of spiral-taught students graduated this year. Contaminating factors such as mixing of students among spiral-taught and comparison cohorts and upper-level project grade inflation (80% of these projects receive A's) made this analysis uninformative. Of the nine graduating seniors who received awards for outstanding project work, however, five were from the spiral-taught curriculum. For that class, only a third of the graduates were in the spiral-taught cohort.

An alternative to probing project performance is to compare grades of comparison and spiral-taught students in upper-level courses. These courses represent the core knowledge of the discipline and include: fluid, heat, and mass transport; kinetics and reactor design; two process design courses; and two unit operations lab courses. A variety of faculty members, course formats, and teaching methods are used in this mix: large lecture, group work, laboratories, and team-based capstone design. WPI awards only four letter grades (A, B, C, and NR)—there is no D grade. The NR (No Record) grade, typically covers the traditional D-F range and is a "faiure" grade that results in no course credit.

In all cases, spiral-taught students received a higher percentage of A's and a lower percentage of C's than comparison students. For the class of 2000, spiral-taught students represented 33% of the class, yet they accounted for 40% of the A's and only 22% of the C's, from a total of eight core junior- and senior-level courses. For the class of 2001, spiral-taught students represented 50% of the class and accounted for 64% of the A's and only 29% of the C's, from a total of five core junior- and senior-level courses. For both cohorts over two years of data, a total of 35 failing grades were earned in all courses examined. Only three of those were from spiral-taught students, and the same student earned all of them.

This data demonstrates the ability of spiral-taught students to perform at higher levels despite different course formats and variable teaching styles and standards in their upper-level courses.

Attitudes About the Curriculum, the Discipline, and the Faculty

Spiral-taught students showed more positive attitudes about chemical engineering and higher confidence in the major than comparison students.

Student course evaluations are required for all WPI courses. A standard form is used that primarily examines student satisfaction with the instructor. We examined the aggregate responses from all sophomore-level chemical engineering courses for sections taught by all instructors. There were no significant differences between spiral instructors and other faculty. In fact, the percent of positive student responses for the spiral curriculum instructors, as a group, was equal to or higher than that for instructors in the traditional sections (*i.e.*, those teaching the comparison cohort).

When the project started, we planned to implement pre/post surveys during each year. During the first implementation year we observed that results from these surveys gave little information, particularly for the time invested administering them to each cohort. We also made a philosophical decision that surveys with closed wording, forced-choice responses, and fixed topics were not appropriate for our project. We felt this type of evaluation tool, which restricts students responses to predetermined questions, did not allow us to probe a range of possible topics and responses from the students' perspectives. Hence, we used open-ended questionnaires for the remainder of the project.

All sophomores were given a questionnaire at the end of each implementation year. Students were asked about their

TABLE 2
Results from End-of-Year Questionnaire
[Number of students responding each year is in ()]

	<i>Spiral-Taught</i>		<i>Comparison</i>	
	<i>97-98</i> <i>(n=14)</i>	<i>98-99</i> <i>(n=15)</i>	<i>97-98</i> <i>(n=18)</i>	<i>98-99</i> <i>(n=11)</i>
Positive comments	45	61	20	27
Number of topics	19	19	9	15
Negative comments	22	38	22	33
Number of topics	12	14	14	16
<i>Confidence in choice of major</i>				
Positive change	12	12	2	10
Negative change	0	1	5	1
No change	0	2	6	0

expectations for the year and whether or not they were met. They were asked about their choice of major and their confidence in pursuing chemical engineering. We asked what were the 2 to 3 most-valuable and the 2 to 3 least-valuable aspects of their sophomore-year classes. Additional questions included estimates of work effort, quality of teaching assistants, and any general comments. A summary of the content analysis of the results is shown in Table 2. We should keep in mind that these responses were taken from a fairly open-ended questionnaire. The numbers in a particular category do not necessarily represent responses to the same questions. They represent relatively spontaneous numbers of mentioned topics, rather than responses to forced-choice questions.

The overall results show that spiral-taught students were more satisfied with their academic experience and more confident with their choice of major than their peers in the comparison section were. There were about twice as many positive comments made by spiral-taught students on a broader number of topics than by comparison students. The positive comments included topics such as group work, lab work, interaction with the professors, and the projects. Many of the negative comments made by spiral-taught students were about problems that they reported improved during the year (such as "kinks" in early course organization and changing professors) and were generally not about the quality of their overall learning experience.

Negative student comments were particularly revealing. Spiral-taught students complained most about their high workload and about the teaching assistants. The comparison students' complaints were often stated in terms of a deficit (not enough application, not enough material covered, not enough group work, not enough projects, not enough individual attention, not being in the spiral class) and were more suggestive of a dissatisfaction with their overall experience.

Retention in CM

Spiral-taught students showed higher retention rates in the major than did comparison students.

Retention is a key issue when new curricula are implemented. We are probably similar to most departments in that the biggest loss of students from the major occurs during the sophomore year. Historically, our retention rate is about 80%, meaning that 20% of the students enrolling in the first chemical engineering course leave the major by the end of their sophomore year.

We found retention was higher during the sophomore year for spiral-taught students compared to the comparison cohort. Table 3 shows the retention data. Note that in 98-99,

retention in the traditional courses was significantly lower than normal while spiral student retention was maintained at 80%. We interviewed many of the students who left the spiral curriculum and found that reasons were typically related to leaving engineering for one of the sciences (chemistry, biochemistry). An interesting anecdote is that one student who left late in the year said she remained in the spiral curriculum so long only because she liked it so much—eventually it became clear that chemical engineering was not her preferred discipline and she switched to civil engineering.

The Process of Learning Chemical Engineering

We are currently involved in a detailed analysis of the problem-solving session videotapes taken during the team competition. These are the two-hour tapes of each team that were not used for judging team solutions. The tapes have all been transcribed and are being analyzed using techniques similar to Linde, *et al.*,^[14] to study the problem-solving process in spiral-taught and comparison teams. Our methodology for this analysis combines the expertise of a developmental psychologist with that of a chemical engineer.^[15]

Preliminary results indicate that the spiral-taught teams exhibited significantly different teamwork skills than did the comparison teams. Since spiral-taught teams presented better solutions, we are interested in characterizing their process and connecting it to our curriculum design.

We observed that spiral-taught teams behaved more like *practicing* chemical engineers attacking a problem, while comparison teams behaved like *students* of chemical engineering. We've observed significant differences in the use of tools of the profession (authority figures, textbooks, published data, etc.) that points to a model of teamwork somewhat different than the traditional engineering model. None of the teams (comparison or spiral) exhibited any evidence of team dysfunction due to typical problems such as dominant individuals (either intellectually or personality-based), gender bias, lack of participation, or lack of motivation. Successful teams, as rated by external judges, had a greater ability to construct a framework for solving the problem. Unsuccessful teams struggled to do so, and such teams were unable to move toward a framework even when individual members seemed capable of starting the process. We are currently articulating the theoretical basis for these observations and formulating an in-depth description of the model and its relation to the new curriculum.

Areas Needing Improvement

Despite the success of the curriculum as described above, we are aware of three areas where improvement is needed. We attempted to incorporate writing into the curriculum to

TABLE 3
Retention Data for
Sophomore ChE Students

<u>Academic Year and Section</u>	<u>Percent Retained</u>	<u>Total Students at Year End</u>
96-97		
No separate sections	80	62
97-98		
Comparison	80	32
Spiral-taught	88	14
98-99		
Comparison	68	17
Spiral-taught	80	16

exploit the writing-to-learn philosophy. But our efforts lacked consistency, and due to time taken to deliver the new curriculum, we could not implement all we had envisioned. Although spiral-taught students had multiple writing opportunities, a concerted program to improve writing was not possible. Some anecdotal evidence from upper-level writing samples supports the notion that we did have some positive impact on spiral-taught students' writing abilities.

We struggled with spiraling the concepts associated with solution thermodynamics. This is some of the most difficult material that sophomores encounter. In fact, many schools do not teach it until the junior year. The optimal time and location in the curriculum for introducing some of these theoretical concepts is not known. We made improvements from the first to the second implementation year, but our sense is that more work is needed to sort out how students may best understand these concepts.

The final project, for both implementation years, was a significantly different and more complex project than any of those earlier in the year. We asked students to design a project that could be used in future course offerings. The technical material involved some topics of chemical engineering (transient material and energy balances) that are not normally a part of the sophomore year. We believe that students showed mastery of the technical material, but they could not translate that knowledge sufficiently into the context of the project. Hence they developed mediocre-to-poor projects regardless of the team. There appears to be a general intellectual limit to their ability to integrate concepts from earlier in the year and extrapolate them to new situations. We are currently examining that limit by analyzing our evaluation data from those projects.

SUMMARY

We believe our assessment results clearly show the benefits of all the educational activities implemented in the spiral curriculum. In fact, we were quite surprised that differences between spiral-taught and comparison cohorts were so dramatic in so many different areas. Results from a variety of measurements and analysis converged upon a consistent answer.

Compared to traditionally taught students, spiral-taught students displayed equal or better understanding of basic chemical engineering principles, were better in teams at solving open-ended problems, had higher satisfaction levels with their academic experience, had higher retention rates, performed better in upper-level courses, and were more confident about their choice of chemical engineering as a major. Although our evaluation plan could not delineate effects of individual curricular improvements, we believe that frequent open-ended project experiences built around a spiral topic structure were the major reasons for project success.

After extensive discussions, the WPI chemical engineering department voted to permanently adopt the curriculum described in this series of three papers for all our sophomore students beginning in the fall of 2001.

ACKNOWLEDGMENTS

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Estimating the Transfer of Oxygen

Continued from page 139.

ferred approach is to tailor the functional form derived from existing correlations in an attempt to maximize the use of the specific information available.

The laboratory exercise also has secondary benefits. First, the exercise bridges the gap between biotechnology and classical chemical engineering. Students are often under the impression that the area of biotechnology represents a radical departure from the chemical engineering principles applied to other industries. This laboratory serves to demonstrate that the "high tech" fields have been developed on the same set of principles as the mature industries. On a practical level, the lab deals with benign materials. As such, there are no fume hood requirements or disposal problems. The lab can easily be extended to examine the effect of other variables, such as temperature, oxygen partial pressure, and liquid volume.

CONCLUSIONS

When faced with a design problem, the chemical engineer often must turn to empirical expressions, generalized through the application of dimensionless groups. But as data become available that are specific to the system of interest, the basic proven empirical expression should be tailored to reflect these data. Extracting the relevant parameters of interest (*i.e.*, $K_L a$) from experimental data generated for this purpose is subjective, based heavily on the assumptions made by the engineer. Although many approaches may be adequate, others may lead to erroneous results. A key variable to consider when analyzing the problem is the influence of the measuring element on the resulting data set.

NOMENCLATURE

a	area available for mass transfer per unit volume of ungasged liquid (m^2m^{-3})
C_G	concentration of oxygen in the gas phase (mol L^{-1})
C_G^0	concentration of oxygen in the gas phase at $t=0$ (mol L^{-1})
C_L	concentration of oxygen in the liquid (mol L^{-1})
C_L^*	concentration of oxygen in the liquid in equilibrium with the gas phase (mol L^{-1})
C_p	concentration of oxygen in the liquid, as measured by the dissolved oxygen probe (mol L^{-1})
d_i	impeller diameter (m)
d_T	tank diameter (m)
D_{O_2}	diffusivity of oxygen in water (m^2s^{-1})
g	acceleration of gravity (m s^{-2})
h_i	height of impeller from bottom of tank (m)
h_L	height of liquid (m)
l_i	length of impeller blades (m)
H^2	Henry's constant for oxygen and water ($\text{mmol L}^{-1} \text{atm}^{-1}$)
K_1	empirical constant
K_L	overall mass-transfer coefficient per unit transfer area,

	based on the liquid phase (m s^{-1})
$K_L a$	volumetric mass-transfer coefficient, based on the liquid volume (hr^{-1})
k_p	$(1 / \tau_p)(\text{s}^{-1})$
n_B	number of baffles
n_i	number of blades on impeller
N	stirring speed (rev s^{-1})
P	power input into ungasged liquid (W)
P_G	power input into gasged liquid (W)
v_s	superficial gas velocity, based on cross section of vessel (m s^{-1})
v_t	terminal rise velocity of a gas bubble (m s^{-1})
w_B	width of baffles (m)
w_i	width of impeller blades (m)
Q	gas flow rate (L s^{-1})
t	time (s)

Greek symbols

$\alpha, \beta, \gamma, \lambda$	exponents in Eqs. (12), (17), and (21)
τ_p	time constant of the dissolved oxygen probe (s)
τ	time constant of the transfer process ($1/K_L a$)(s)
μ_f	liquid viscosity (cp)
ρ_f	liquid density (kg m^{-3})
σ_f	surface tension at gas-liquid interface (mN m^{-1})

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UNDERGRADUATE PROCESS CONTROL

Clarification of Some Concepts

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Teaching undergraduate process control can be an enjoyable experience for an instructor given the wide range of quality chemical engineering textbooks that are now available.^[1-6] After teaching the course a couple of times, however, I felt there was still a need for clarification of some fundamental concepts, especially in the areas of frequency response and stability. In this article I hope to achieve such a clarification through some simple, yet illustrative, examples.

FREQUENCY RESPONSE: ONLY FOR STABLE SYSTEMS?

In the context of process control, the frequency response is usually associated with the response of a linear, time invariant (constant coefficient) system to a sinusoidal input. In the most common way of “deriving” the frequency response result, the output response is shown to be a sinusoidal function of the same frequency (ω) as the input, *once the transients have died out*. Further, the ratio of the amplitude of the output to that of the input, called the amplitude ratio (AR), is shown to be equal to $|G(j\omega)|$, while the phase difference (ϕ) between the output and the input is shown to be $\arg[G(j\omega)]$, where $G(s)$ is the transfer function representation of the system of interest and $j=\sqrt{-1}$.

Thus, the frequency response calculation is reduced to the calculation of the magnitude and phase of the complex number, $G(j\omega)$, as a function of the frequency. This information is usually represented in the form of a Bode diagram or a Nyquist plot.

The key point of our discussion is the condition

“once the transients have died out.”

Clearly, this happens if the system is stable, *i.e.*, if all the poles of the transfer function $G(s)$ lie in the left half (of the

complex) plane (LHP). Thus it might appear that frequency response makes sense only for stable systems. But we do find Bode diagrams and Nyquist plots for the pure capacity ($G(s)=A/s$) and the PI controller, $G(s)=[K_c(\tau_1s+1)]/\tau_1s$, both of which are (open-loop) unstable.

Do these diagrams mean anything then? In the case of the pure capacity system, one can show that the response to a sinusoidal input is bounded and is a superposition of a constant and a sinusoidal function whose amplitude and phase are in fact provided by $G(j\omega)$, as for a stable system. (It should be noted that a system with a zero pole is to be regarded as unstable in spite of a bounded response to a sinusoidal input. Recall that the step response of such a system grows with time.)

But what about a system with a pole in the right half plane (RHP) for which the response to a (bounded) sinusoidal input will have a time-growing component arising out of the unstable pole? Does the Bode diagram (or the Nyquist plot) for such a system obtained from the corresponding $G(j\omega)$ have any meaning?

The answer to the last question is “yes.”

The common way of deriving the frequency response result is only a method of measuring the frequency response for stable systems and does not constitute a fundamental

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definition of it. The fundamental definition is provided by a basic result of linear systems theory.^[7] There exists a periodic solution for a linear time invariant system subjected to a periodic forcing; this periodic solution has the same frequency as that of the input forcing, and its amplitude and phase at the particular frequency are determined (as explained above) from the complex number $G(j\omega)$. This result holds whether the system is stable or not.

In general, the response of a linear system to a periodic forcing will be the superposition of the periodic solution and a non-periodic component, and the frequency response is defined with respect to the periodic component. Thus, the Bode diagram for an unstable system makes sense in that it represents the same relationship between the periodic component of the (output) response and the input periodic forcing as it does for a stable system.

This point is not of minor significance as it gives universal status to Bode diagrams or Nyquist plots as signatures of systems they represent, be they stable or unstable. The open-loop method of measuring the frequency response (after waiting for the transient to die out) will not work for unstable systems (pure capacity being an exception).

In the next section, we point out two possible methods of measuring the frequency response of unstable systems—one an open-loop method and the other a closed-loop method. Although both methods are valid in principle, the latter is more practicable. The reasons are outlined below.

Frequency Response of Unstable Systems

We illustrate the procedures through a simple system with one unstable pole

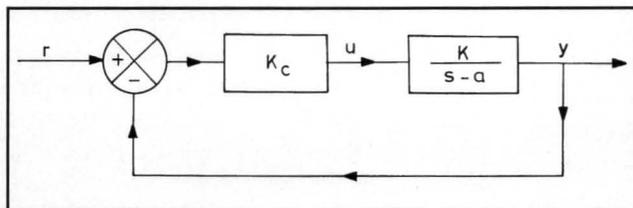
$$G_o(s) = \frac{K}{s-a} \quad (1)$$

Open-Loop Method

For the Open-Loop Method we consider a sinusoidal input

$$u(t) = A_u \sin(\omega t + \phi_u) \quad (2)$$

The response of the system to this input can be shown (for instance, by a straightforward Laplace inversion) to be



After teaching [undergraduate process control] a couple of times, I felt there was a need for clarification of some fundamental concepts, especially in the areas of frequency response and stability. In this article I hope to achieve such a clarification through some simple, yet illustrative, examples.

$$y(t) = \frac{KA_u(\omega \cos \phi_u + a \sin \phi_u)e^{at}}{a^2 + \omega^2} + A_u |G_o(j\omega)| \sin\{\omega t + \phi_u + \arg[G_o(j\omega)]\} \quad (3)$$

This suggests a way of “stabilizing” the response by choosing ϕ_u such that

$$\omega \cos \phi_u + a \sin \phi_u = 0 \quad (4)$$

so that only the *stable* periodic component of the solution remains, enabling the determination of its amplitude and phase. In practice, thus, one is left to choose a unique value of ϕ_u (between 0 and 2π) for each ω ; this can be problematic given that the value of the unstable pole, a , is not known *a priori*. Hence, we discuss a more practicable method involving closed-loop stabilization.

Closed-Loop Method

We consider the same first-order unstable system. It is easy to show that the system can be stabilized in a feedback loop using a proportional controller of gain K_c greater than a/K (Figure 1 illustrates the scheme). In fact

$$\frac{y(s)}{r(s)} = \frac{K_c K}{s+b} \equiv G_{CL}(s) \quad (5)$$

where $b = K_c K - a > 0$.

If a sinusoidal variation is given in the reference signal, r , *i.e.*,

$$r(t) = A_r \sin \omega t \quad (6)$$

then we can show that (by Laplace inversion, for instance)

Figure 1. An open-loop unstable system in a feedback loop with a proportional controller.

$$y(t) = C_1 e^{-bt} + A_y \sin(\omega t + \phi_y) \quad (7)$$

where

$$C_1 = \frac{K_c K_A r \omega}{\omega^2 + b^2}; \quad A_y = A_r |G_{CL}(j\omega)|; \quad \phi_y = \arg[G_{CL}(j\omega)] \quad (8)$$

The signal $u(t) = K_c[r(t) - y(t)]$ can be expressed as

$$u(t) = -K_c C_1 e^{-bt} + A_u \sin(\omega t + \phi_u) \quad (9)$$

It is possible to show that

$$\frac{A_y}{A_u} = |G_o(j\omega)| \quad \text{and} \quad \phi_y - \phi_u = \arg[G_o(j\omega)] \quad (10)$$

i.e., the amplitudes and the phases of the “input” and the “output” signals of the unstable system, $G_o(s)$, are related as before by the complex number $G_o(j\omega)$. The stabilization effect is noted in the e^{-bt} term (note: $b > 0$) in both y and u in contrast to the open-loop case where we get the time-growing term, e^{at} , in the output (for the same input $A_r \sin \omega t$). For concreteness and simplicity, we illustrate the above result with a numerical example.^[8] We choose

$$G_o(s) = \frac{2}{s-1} \quad (11)$$

It is easy to see that a unity gain ($K_c = 1$) proportional controller stabilizes the above system in a feedback loop. In fact

$$\frac{y(s)}{r(s)} = \frac{2}{s+1} \quad (12)$$

If we choose the input to be

$$r(t) = 0.5 \sin 2t \quad (13)$$

then we can show that

$$y(t) = \frac{2}{5} e^{-t} + (0.2)^{1/2} \sin[2t - 1.11(\text{rad})] \quad (14)$$

Further

$$u(t) = r(t) - y(t) = \frac{-2}{5} e^{-t} + 0.5 \sin[2t + 0.93(\text{rad})] \quad (15)$$

and

$$|G_o(2j)| = \frac{2}{\sqrt{5}} \quad \text{and} \quad \arg[G_o(2j)] = -2.04 \text{ rad} \quad (16)$$

Thus, we see that

$$|G_o(2j)| = \frac{A_y}{A_u} \quad \text{and} \quad \arg[G_o(2j)] = \phi_y - \phi_u \quad (17)$$

Of course, the above analysis is based on a given system transfer function. This is not known *a priori* and, in fact, the purpose of the frequency response experiment is to determine the transfer function. But what one has to do is to tune the proportional controller to obtain a stable system. Then, for a known sinusoidal input, $r(t)$, at various frequencies, one would have to measure the amplitude and phase of both

$u(t)$ and $y(t)$ (after the transients die out) to construct the transfer function, $G_o(s)$.

FREQUENCY RESPONSE AND STABILITY CRITERIA

We now turn to another aspect of frequency response and stability, the famous Nyquist stability criterion. The Nyquist criterion helps one to infer the stability of a feedback control system from the Nyquist (polar) plot of the loop transfer function, $G_L(s)$, which is the product of the transfer functions of all the elements in the control loop. The advantage of stability criteria based on frequency response is their ability to deal with non-polynomial $G_L(s)$ that the Routh-Hurwitz criteria cannot treat rigorously. This advantage is particularly relevant to chemical engineering systems that often contain a time-delay element.

Most chemical engineering textbooks on process control do not give as much prominence to the Nyquist criterion as they do to the Bode stability criterion, which is easier to use. An exception is the Luyben^[2] book where a detailed discussion with illustrative examples can be found. It is to be noted that the Bode criterion is not general and specifically cannot be applied in cases where the Bode diagram for $G_L(s)$ is not monotonically decreasing. It is our objective here to highlight the potential sources of error in the application of the Nyquist criterion. It is not uncommon to find special statements of the criterion that might work in many cases but fail to yield the correct result for at least some systems. Often, these special statements are not accompanied by the conditions under which they hold. Thus it is desirable to always use the general form of the criterion that is given below.

Let N be the number of net rotations of the Nyquist plot of $G_L(s)$ ($-\infty < \omega < \infty$) about the point $(-1, 0)$. This is the net angle traced out by the line segment from $(-1, 0)$ to the Nyquist plot as the frequency changes from $-\infty$ to ∞ . The sign convention is a positive value for N if the net rotation is in the counter-clockwise direction and negative if it is in the clockwise direction. Let P_R be the number of poles of $1+G_L(s)$ (note that this is the same as the number of poles of $G_L(s)$) in the RHP. Then

$$Z_R = P_R - N \quad (18)$$

where Z_R is the number of zeros of $1+G_L(s)$ in the RHP. Hence, Z_R is the number of roots of the characteristic equation $1+G_L(s)=0$ that lie in the RHP. Clearly, Z_R must be zero for a stable system.

It is not our objective here to give a proof of the above statement (see, for instance, Ref. 9), but we illustrate its proper use through a simple example. In our opinion, the following points are crucial:

- While the portion of the Nyquist plot from $-\infty$ to 0 is

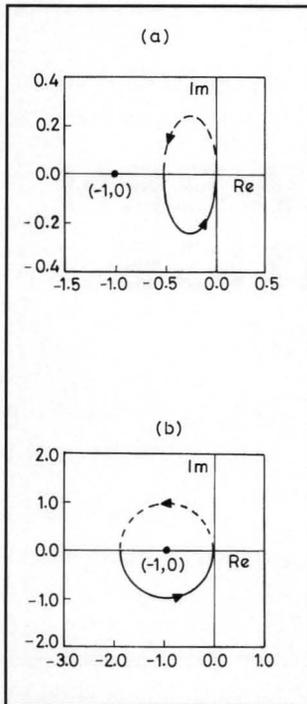


Figure 2.
Nyquist plots for
a)

$$G_{L1}(s) = \frac{1}{2(s-1)}$$

and
b)

$$G_{L2}(s) = \frac{2}{(s-1)}$$

The dotted (---) portion is for $-\infty < \omega \leq 0$ while the solid (—) portion is for $0 \leq \omega < \infty$. The direction of the arrow is in the direction of increasing ω .

simply the mirror image (about the real axis) of the portion from 0 to ∞ , not using the full plot can lead to erroneous conclusions.

- The precise meaning of the commonly used notion of “encirclement” about the (-1,0) point must be understood. It is not uncommon^[6,9] to have cases where the (-1,0) point is entirely within Nyquist plot and hence appears “encircled,” but the net encirclement is, in fact, zero. Further, the direction of encirclement is crucial. Encirclement in itself does not necessarily mean that the closed-loop system is unstable.
- The number of RHP poles of $G_L(s)$ must be known.

We demonstrate the above points by choosing a simple system—the same one we chose in the previous section

$$G_o(s) = \frac{2}{s-1} \quad (19)$$

in a feedback loop with a proportional controller of gain $K_{c1}=1/4$ and $K_{c2}=1$. It is easy to see that the first control system is unstable, while the second is stable, by considering the characteristic equations $1+G_{L1}(s)=0$ and $1+G_{L2}(s)=0$, respectively. But our objective here is in the application of the Nyquist criterion.

Figure 2a shows the Nyquist plot of

$$G_{L1}(s) = \frac{2K_{c1}}{s-1} = \frac{1}{2(s-1)} \quad (20)$$

The figure clearly shows that $N=0$ as the net angle traced out

by the full Nyquist plot (with reference to the (-1,0) point) is zero. Since $P_R=1$, we get

$$Z_R = P_R - N = 1 - 0 = 1 \quad (21)$$

Thus the closed-loop system is unstable with one root of the characteristic equation in the RHP. Note here that even though the Nyquist plot does not encircle the (-1,0) point, the closed-loop system is unstable.

Figure 2b shows the Nyquist plot for

$$G_{L2}(s) = \frac{2}{s-1} K_{c2} = \frac{2}{s-1} \quad (22)$$

Here the Nyquist plot encircles (-1,0) once. Note that the net angle traced is 2π , but this is in the counterclockwise direction, implying that $N=1$. Again, since $P_R=1$, we obtain

$$Z_R = P_R - N = 0 \quad (23)$$

Thus the closed-loop system is stable, even though the Nyquist plot encircles the (-1,0) point. Note further that if we restrict ourselves to the 0 to ∞ segment, we will not see any encirclement.

Thus, we have highlighted the aspects we set out to illustrate—the importance of considering the entire frequency range ($-\infty$ to ∞), the importance of the direction of encirclement, and the necessity of knowing the number of unstable poles of $G_L(s)$.

CONCLUSIONS

We have clarified the concept of frequency response for linear time-invariant systems, demonstrating its validity for unstable systems as well. We have also highlighted some pitfalls in the use of the Nyquist criterion and pointed out how to avoid them.

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THE INTERFACE BETWEEN ChE AND MATHEMATICS

What Do Students Really Need?

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The Mathematical Association of America (MAA), through its Committee on the Undergraduate Program in Mathematics (CUPM), is conducting a Curriculum Foundations Project, a major analysis of the undergraduate mathematics curriculum. The goal of the project is to develop a curriculum document that will assist college mathematics departments as they plan their programs for the next decade. Historically, CUPM curriculum recommendations have had a significant influence on the design of undergraduate mathematics programs. These important and influential guidelines were last revised in 1981. Therefore, the CUPM curriculum guidelines need to be reconsidered; such a review and the resulting recommendations are likely to have widespread impact on the teaching of undergraduate mathematics.

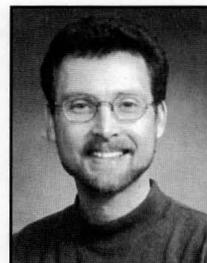
Given the impact of mathematics instruction on engineering, the sciences, and the quantitative social sciences (especially instruction during the first two years), significant input from these partner disciplines is needed to inform the MAA curriculum document. The CUPM subcommittee on Calculus Reform and the First Two Years (CRAFTY) gathered much of this necessary information between Fall 1999 and Spring 2001 through a series of invitational disciplinary workshops funded and hosted by a wide variety of institutions (see Table 1).

Each workshop is focused on a particular partner discipline or on a group of related disciplines, the objective being a clear, concise statement of what students in that area need to learn in their first two years of college mathematics. The workshops are not intended to be dialogues between mathematics and the partner disciplines, but rather a dialogue among representatives of the discipline under consideration,

with mathematicians there only to listen to the discussions and to provide clarification on questions about the mathematics curriculum. For this reason, almost all of the individuals invited to participate in each workshop are from the partner disciplines.

The major product of each workshop is a report or group of reports summarizing the recommendations and conclusions of the workshop. These are written by the representatives from the partner disciplines, with the mathematics community as the primary audience, and they address a series of questions formulated by CRAFTY (see Table 2). Uniformity of style is achieved across the reports by using the same basic questions for each workshop. Having a common list of questions also aids in comparing the reports of different workshops. The questions are simply designed to guide the workshop discussions, however, and therefore are

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Susan L. Ganter is Associate Professor of Mathematical Sciences at Clemson University. She has directed several local and national evaluation studies, including a recent residency at the National Science Foundation in which she investigated the national impact of the calculus reform initiative and helped to develop the evaluation plan for the Institution-wide Reform Program in the Division of Undergraduate Education.

intentionally vague. In addition, workshop participants are asked to focus primarily on the first question category, "Understanding and Contents," with the other questions being of secondary importance.

The reports from each workshop are then widely circulated within the specific disciplines, as well as in the mathematics community, in order to solicit a broad range of comments. At the completion of this process in the spring of 2001, the reports will be published and used in the formulation of the MAA curriculum document. A curriculum conference that includes invitees from all disciplines will be convened in Fall 2001 to synthesize the workshop findings and begin writing the MAA curriculum document, scheduled to be published in 2002.

In addition to providing input into the larger CUPM review, the reports serve as valuable resources for initiating discussions at individual institutions between mathematics departments and partner disciplines. Some mathematics departments have already begun using the reports to stimulate

interdepartmental discussions. Such discussions, as well as those at the CRAFTY workshops, generate good will between mathematicians and colleagues in partner disciplines. In general, colleagues from partner disciplines value mathematics and welcome the opportunity to state their views about mathematics education, provided their opinions are taken seriously. Promoting and supporting informed discussions with the partner disciplines may ultimately be the most important outcome of the MAA Curriculum Foundations Project.

THE CRAFTY ENGINEERING WORKSHOP AT CLEMSON UNIVERSITY

One of the CRAFTY workshops was sponsored and hosted by Clemson University on May 4-7, 2000. It focused on the needs of engineering from the first two years of college

TABLE 1
MAA Curriculum Foundations Workshops

Physics and Computer Science

Bowdoin College • Maine • Oct. 28-31, 1999
William Barker: barker@bowdoin.edu

Interdisciplinary (Math, Physics, Engineering)

USMA • West Point • Nov. 4-7, 1999
Don Small: ad5712@usma.edu

Engineering

Clemson University • South Carolina • May 4-7, 2000
Susan Ganter: sganter@clemson.edu

Health-Related Life Sciences

Virginia Commonwealth University • May 18-20, 2000
William Haver: whaver@atlas.vcu.edu

Technical Mathematics (at two sites)

Los Angeles Pierce College • California • Oct. 5-8, 2000
Bruce Yoshiwara: byoshiwara@hotmail.com
J. Sargeant Reynolds Community Col. • Virginia • Oct. 12-15, 2000
Susan Wood: swood@jsr.cc.va.us
Mary Ann Hovis: hovisma@lrc.tec.oh.us

Statistics

Grinnell College • Oct. 12-15, 2000
Thomas Moore: mooret@math.grin.edu

Business, Finance and Economics

University of Arizona • Arizona • Oct. 28-29, 2000
Deborah Hughes Hallett: dhh@math.arizona.edu
William McCallum: wmc@math.arizona.edu

Mathematics Education

Michigan State University • Michigan • Nov. 1-3, 2000
Sharon Senk: senk@pilot.msu.edu

Biology and Chemistry

Macalester College • Nov. 2-5, 2000
David Bressoud: bressoud@macalester.edu

Mathematics Preparation for the Major

Mathematical Sciences Research Institute • Feb. 9-11, 2001
William McCallum: wmc@math.arizona.edu

TABLE 2

MAA Curriculum Foundations Workshop Questions

Understanding and Content

- What *conceptual mathematical principles* must students master in the first two years?
- What *mathematical problem-solving skills* must students master in the first two years?
- What broad *mathematical topics* must students master in the first two years?
What *priorities* exist between these topics?
- What is the desired *balance* between *theoretical understanding* and *computational skill*?
How is this balance achieved?
- What are the *mathematical needs of different student populations* and how can they be fulfilled?

Technology

- How does *technology affect* what mathematics should be learned in the first two years?
- What *mathematical technology skills* should students master in the first two years?
- What different mathematical technology skills are required of *different student populations*?

Instructional Interconnections

- What impact does *mathematics education reform* have on instruction in your discipline?
- How should *education reform in your discipline* affect mathematics instruction?
- How can *dialogue* on educational issues between your discipline and mathematics best be maintained?

Instructional Techniques

- What are the *effects of different instructional methods* in mathematics on students in your discipline?
- What instructional methods best *develop the mathematical comprehension* needed for your discipline?
- What guidance does *educational research* provide concerning mathematical training in your discipline?

mathematics instruction. The workshop had thirty-eight invited participants, with roughly equal representation from each of four areas in engineering (chemical, civil, electrical, mechanical) and mathematics. The workshop resulted in four documents, one for each of the four engineering areas, addressing the MAA questions specified at the outset of the workshop.

This paper focuses on the recommendations of the chemical engineering group. It is not intended to be a definitive document, but rather a working paper that generates discussion among chemical engineers in order to provide additional feedback for the mathematics community. Therefore, the authors welcome comments and additional ideas.

REPORT OF THE CHEMICAL ENGINEERING GROUP

The Chemical Engineering group members are listed in Table 3.

What Chemical Engineers Do

Since this report was originally written for mathematicians, an appropriate introduction is to discuss what chemical engineers do, why mathematics is needed, and how it is used. A reasonably broad definition is that *chemical engineers design materials and the processes by which materials are made.*

Traditionally, chemical engineers have been associated with the petroleum and large-scale chemical industries, but (especially in recent years) chemical engineers have also been involved in pharmaceuticals, foods, polymers and materials, microelectronics, and biotechnology. The core subjects that underlie and unify this broad field are thermodynamics, chemical reaction processes, transport processes (*i.e.*, the spatial and temporal distribution of mass, momentum, and energy) and process dynamics, design, and control.

On top of this fundamental framework, a central emphasis of chemical engineering education is *model building and analysis*. A good chemical engineer brings together the fundamentals to build and refine a mathematical model of a process that will help him or her understand and optimize its performance. To be good at model building and analysis, students must have at hand the mathematical background to understand and work with the core scientific areas, as well as to find solutions to the final model that they build. In this context, the “solution” to a mathematical problem is often in the *understanding* of the behavior of

the process described by the mathematics, rather than the specific closed form (or numerical) result.

Here is an example: A starting point for understanding any process is writing down the conservation laws that the system or process satisfies...for conserved quantities, accumulation = input - output. Depending on the level of detail of the model, this equation might be, for example, a large set of linear algebraic equations that determine the relationships between fluxes of chemical species throughout the process (a species balance), or it might be a set of parabolic partial differential equations governing the temperature and composition of the fluid in a chemical reactor. In the thermodynamics of multiphase systems, energy is conserved but takes on a variety of forms; a good knowledge of multivariable differential calculus is essential here to keep track of everything.

Mathematics for Chemical Engineering

The purpose of the original report was not to prescribe the mathematics curriculum—chemical engineers do not want mathematics instruction to provide only what students can “get by” with knowing. Nor is it appropriate to come down on either side of the “traditional” vs. “reform” debate—it is likely that both sides are right, to an extent. Instead, some general thoughts on subject matter and emphasis are presented here.

Precalculus Foundations

By foundations, we mean

- *Basic knowledge of families of functions (polynomial, exponential,...) in terms of data, graphs, words and equations, basic trigonometric identities and geometry, properties of logarithms, etc.*
- *Equations, inequalities*
- *Basic logic and algorithms*
- *Small linear systems of equations*
- *Coordinate systems*
- *Basic arithmetic and manipulation skills*

Mastery of the above areas is crucial. Probably the most important thing the mathematics community can do here is to actively investigate the pedagogy of K-12 education—to help sort out which “reforms” are productive from those that are merely “fads” and to encourage schools not to neglect the education of the more mathematically inclined students by focusing the curriculum too narrowly on the average performer. Another impor-

TABLE 3
Chemical Engineering Group Members

- **Jenna P. Carpenter** • Interim Academic Director, Chemical Engineering, Civil Engineering and Geosciences • Louisiana Technological University
- **Michael B. Cutlip** • Professor of Chemical Engineering and Director of the Honors Program • University of Connecticut
- **Michael D. Graham** • Associate Professor of Chemical Engineering • University of Wisconsin-Madison (discussion leader/recorder)
- **Anton J. Pintar** • Associate Professor of Chemical Engineering • Michigan Technological University
- **Jan A. Puszynski** • Professor of Chemistry and Chemical Engineering • South Dakota School of Mines and Technology

tant role here is to provide programs that help K-12 mathematics teachers understand some applications of the mathematics that they teach (engineering faculty should do much more here).

Linear Mathematics

Chemical engineering students would benefit from earlier exposure to the basics of linear systems in \mathbb{R}^N , particularly

- *The geometry of linear spaces*
- *Vector algebra (especially in 3D)*
- *$Ax = b$ (existence and uniqueness, Gaussian elimination, geometric interpretation, over- and underdetermined systems, and least squares problems)*
- *$Ax = \lambda x$ (characteristic polynomial and diagonalization, Jordan form, range and nullspace of A , geometry)*

At the University of Wisconsin-Madison, for example, there is a course on “linear mathematics” that introduces these notions and applies them to systems of ordinary differential equations (see next section). Many chemical engineering students take this in lieu of the traditional differential equations class.

Calculus and Differential Equations

The importance of visualization in calculus cannot be overemphasized, especially as a guide to differential and vector calculus in multiple dimensions, plotting (*e.g.*, what function is linear on a log-log plot?), working in cylindrical and spherical coordinate systems, and converting between coordinate systems. Somewhat less time could be spent on techniques for evaluating complicated integrals, with the time spent instead on, for example, visualizing the application of the chain rule in multiple dimensions. Understanding of truncated Taylor series for local approximation of functions is very important and should be seen early and often. In differential equations, a thorough knowledge of linear constant coefficient systems (initial value problems and boundary value problems; see previous section) is preferable to emphasis on existence theory and series solutions for non-constant coefficient problems. Some qualitative theory for nonlinear systems is also desirable.

Probability and Statistics

Alumni surveys typically show that this is the most common application of mathematics for the practicing chemical engineer with a bachelor’s degree, in addition to the extensive use of spreadsheets. Key issues here include parameter estimation, experimental design, sampling, and the origins and properties of various distribution functions.

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Students interested in graduate school should be encouraged by their mathematics professors, as well as their engineering advisors, to take additional mathematics courses. A final general comment: students should have some idea of the power of a theorem, but for engineers, concepts are more

. . . [the] discussions . . . generate good will between mathematicians and colleagues in partner disciplines. In general, colleagues from partner disciplines value mathematics and welcome the opportunity to state their views about mathematics education, provided their opinions are taken seriously.

important than proofs. In other words, it is appropriate for chemical engineering students to learn mathematical facts without always seeing the associated proofs.

Technique and Technology

A fair amount of the discussion at the MAA engineering workshop, within the chemical engineering group and others, centered around the use of technology in the mathematics courses for engineers. In the discussions, “technology” meant a number of different things, from numerical methods to graphing calculators to symbolic manipulation packages. We’d like to emphasize here some points to be kept in mind when thinking of the introduction of these tools into mathematics courses. We do this in the form of responses to two questions, representing both sides of the issue (admittedly, these questions are straw men):

“My laptop can do that. Why should I learn to do it by hand?”

- *Sense of form of mathematical expressions, understanding of what manipulations are available, facility with these manipulations*
- *Fluency in the language of mathematical concepts*
- *Appreciation and recognition of mathematical rigor*
- *Discipline, maturity, confidence of mastery*
- *Closed form results are best, if available*
- *Recognition of limitations of closed form results, where things get difficult*
- *Knowledge of what computers do*

“Use of computers dumbs down the mathematics course—why use them?”

- *Solution of realistic (complex) problems, many of which involve numerical solutions. In upper-level courses, extensive use is made of programs such as MATLAB, Octave (available at <www.che.wisc.edu/octave>), MathCad, Mathematica, and Polymath*

- *Efficient exploration of solution and design space*
 - *Visualization, especially in multidimensional and vector calculus*
- *Relief from tedium*
- *Confidence in results derived by hand*

Ultimately, the technology should take a back seat in mathematics courses until it becomes necessary for solving interesting problems. For example, in a linear algebra course, students should be able to do LU decomposition of a 3x3 system by hand before they are shown that a computer algebra system can complete the process with one command. At the same time, it is useful to point out the relationship between numerical techniques and exact ones (e.g., a Riemann sum can be evaluated numerically to approximate an integral). Students should have a solid understanding regarding limitations of numerical methods and their accuracy. They should clearly see the power of analytical solutions when such solutions can be found.

A Suggestion for Coupling Mathematics and Engineering Education

One set of issues that arose repeatedly in the MAA engineering workshop discussions was the concern that students do not see connections between mathematical tools and concepts and the wide utility of these in engineering. A related concern was the time lag between exposure to mathematics and its application to the solution of real engineering problems. The notion of “just-in-time” learning was discussed, and the suggestion was made that mathematics courses be more application- or example-driven and be more evenly spread through the curriculum, rather than “front loaded” into the first two years. The chemical engineering group shared these concerns, but also thought that

- 1) *Part of the beauty and power of mathematics is that it is example-independent—calculus applies to economics just as it does to mechanics*
- 2) *The time spent developing the background for engineering applications is time not spent on mathematical principles and tools*
- 3) *A straightforward “just-in-time” approach will not satisfy all engineering majors (e.g., electrical engineers do not need Laplace transforms at the same time as chemical engineers).*

An alternative structure can be considered for addressing these concerns, which are essentially about how to connect mathematics and engineering in the students’ minds. Specifically, the college mathematics curriculum could include *discipline specific supplements*, especially in the calculus sequence. These could be workbooks or web pages containing, for example,

- *Engineering background material, e.g., some basic*

thermodynamics, and how specific mathematical principles and/or tools (such as total differentials and partial derivatives in several dimensions) are used

- *Exercises or projects integrating mathematics and engineering*
- *Additional discipline-specific emphases, e.g., trigonometric identities and manipulations for electrical engineering students.*

These could be used independently by the students, or used in a one-credit course running in parallel with the calculus courses, or simply be resources for mathematics instructors wishing to gain perspective on engineering applications or bring engineering applications into the mathematics classroom. This is perhaps overambitious, but certainly worth considering. It was suggested that, within chemical engineering, CACHE (Computer Aids for Chemical Engineering <www.CACHE.org>) could play a role in studying this possibility in conjunction with MAA.

CONCLUDING REMARKS

It is clear that the application of mathematical concepts and the generation of mathematical solutions to engineering problems are essential to the educational programs of all undergraduate engineering students. Enhanced cooperation between mathematics faculty and engineering faculty can lead to a better experience for our students. Without exception, the participants felt that the workshop was a very productive way to promote dialogue between the mathematics and engineering education communities and encouraged the organization of more workshops of this type. Another venue that mathematicians can explore is the American Society for Engineering Education <www.asee.org>, which has a mathematics division. On the other hand, it may be productive for engineering educators to attend MAA meetings.

Perhaps most importantly, mechanisms need to be implemented to promote interaction between engineering and mathematics faculty within individual universities—good relationships at this level will enable mathematics faculty to understand what material the engineering faculty would like to see reinforced and emphasized, as well as enabling engineering faculty to gain a better understanding of the issues surrounding mathematical preparation of entering freshman engineering majors.

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AUTHOR GUIDELINES

This guide is offered to aid authors in preparing manuscripts for Chemical Engineering Education (CEE), a quarterly journal published by the Chemical Engineering Division of the American Society for Engineering Education (ASEE).

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