CEE

chemical engineering education

VOLUME 33 • NUMBER 3 • SUMMER 1999

Carol Hall

of North Carolina State University

and Chemical Engineering at

Clemson University

Chemical Engineering Division, American Society for Engineering Education

American Institute of Chemical Engineers

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).

CEE publishes papers in the broad field of chemical engineering education. Papers generally describe a course, a laboratory, a ChE department, a ChE educator, a ChE curriculum, research program, machine computation, special instructional programs, or give views and opinions on various topics of interest to the profession.

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University of Florida, Gainesville, FL 32611-6005

Chemical Engineering Education
Volume 33 Number 3 Summer 1999

CHEMICAL ENGINEERING EDUCATION (ISSN 0009-2479: USPS 101900) is published quarterly by the Chemical Engineering Division, American Society for Engineering Education, and is edited at the University of Florida. Annual subscription costs $40.00. Correspondence regarding editorial matter, circulation, and changes of address should be sent to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL 32611-6005. *Defective copies replaced if notified within 120 days of publication. Write for information on subscription costs and for back copy costs and availability. POSTMASTER: Send address changes to CEE, Chemical Engineering Department., University of Florida, Gainesville, FL 32611-6005. Periodicals Postage Paid at Gainesville, Florida.*

Clemson University

Ron Grant and Charlie Gooding
Clemson University • Clemson, SC 29634-0909

Clemson University, the land-grant institution of South Carolina, is the realization of a long-held dream of its founder, Thomas Green Clemson. A Pennsylvania native, Clemson developed a profitable career as a young consulting and mining engineer in Paris, Philadelphia, and Washington. In 1838 he married the daughter of South Carolina statesman John C. Calhoun, and over the next fifty years he developed an abiding love for upstate South Carolina and an intense interest in the application of scientific principles to improve agriculture. Clemson managed Calhoun's Fort Hill plantation, wrote and published extensively on agricultural chemistry, and eventually served as U.S. Superintendent of Agricultural Affairs. He bought Fort Hill in 1866 after Calhoun's death and spent the last years of his life developing plans to create a "high seminary of learning to benefit the agricultural and mechanical arts." Outliving his wife and children,Clemson left the bulk of his estate to South Carolina upon his death in 1888, with specific instructions in his will leading to the establishment

The Clemson Chemical Engineering Class of 1999 . . .

and evidence of a midnight prank when students rearranged the letters on Earle Hall to indicate that Clemson has the hottest chemical engineering program in the country.

of Clemson College on the Fort Hill site. The Calhoun mansion remains in the center of campus today—a historic landmark to Clemson's vision. The small town that borders the campus also bears his name.

Chemical engineering was first introduced as a course of study at Clemson in 1917. At that time there was no chemical engineering department or faculty, and the core of the curriculum was drawn from courses in mathematics, physics, chemistry, and mechanical engineering. In the spring of 1923, four students completed the prescribed course of study and became Clemson's first chemical engineering graduates. The Department of Chemical Engineering was formally established in 1946, and the undergraduate program has been accredited by ABET since 1959. The Master of Science program was begun in 1960, and the Doctor of Philosophy program was added in 1962. In 1965 the department awarded the first PhD in engineering in the State of South Carolina.

FACILITIES AND FACULTY

Earle Hall was donated to the University by the Olin Charitable Trust in 1958 specifically to house chemical engineering. The 50,000-square-foot facility contains four classrooms, an auditorium, a library, a student lounge, a seminar room, a shop, a 9,000-square-foot unit operations lab, several dedicated research labs, and faculty, graduate student and administrative offices,

Over the past forty years, Earle Hall has undergone many renovations, the most recent being the conversion of the old auditorium into a modern, 68-seat seminar and teaching facility, complete with multimedia projection equipment and a network connection at each seat. As the department has matured, it has benefited enormously from the generous support of alumni and corporate benefactors. Several research labs have been refurbished in recent years to accommodate growing programs and new faculty additions, and the Dow Chemical Company Unit Operations Lab is currently undergoing additional equipment upgrades and modifications.

The faculty of the department is also undergoing a transition, with four new additions in the last few years, all with youthful exuberance and excellent credentials. David Bruce and Mike Kilbey joined the deprtment in 1995, Scott Husson arrived in 1998, and Graham Harrison will be on board in August 1999, after completing a post-doc at the University of Melbourne. The faculty now totals twelve tenured and tenure-track faculty members involved full time in the teaching and research programs of the department (see Table 1). Another new colleague, currently in industry, will also join the faculty later this year. In addition, Y. T. Shah is Senior Vice Provost and Chief Research Officer of the University, Steve Melsheimer is Associate Dean for Undergraduate Studies in the College of Engineering and Science, and Bill Beckwith is Director of the General Engineering Program. Professor Emeritus Joe Mullins also remains active in the support of numerous teaching and research activities of the department.

UNDERGRADUATE STUDIES

Over the last decade the senior chemical engineering class at Clemson has averaged forty-five students per year, and our recent graduates have taken jobs with over 100 different companies. About

TABLE 1
Faculty

Charles H. Barron Jr. (DSc, University of Virginia, 1963)
Polymer reaction engineering, analysis of the effects of physical interactions on molecular weight distribution; information systems for design database development

David A. Bruce (PhD, Georgia Institute of Technology, 1994)
Catalyst development for the petrochemical and pharmaceutical industries and for pollution abatement, chiral zeolites, solid superacids, supported metal complexes

Dan D. Edie (PhD, Univ. of Virginia, 1972) Dow Chemical Professor
Director of the Center for Advanced Engineering Fibers and Films
Polymer processing, formation and characterization of high performance fibers and composite materials, mathematical modeling, rheology

Charles H. Gooding (PhD, North Carolina State University, 1979)
Department Chair
Mass transfer, particularly application and modeling of membrane separation technologies

James M. Haile (PhD, University of Florida, 1976)
Molecular dynamics and thermodynamics, the use of computer simulation techniques to determine thermodynamic and transport properties in fluids

Graham M. Harrison (PhD, Univ. of California, Santa Barbara, 1997)
Non-Newtonian fluid mechanics, optical and mechanical techniques for experimental characterization of polymers, molecular-based constitutive equations

Douglas E. Hirt (PhD, Princeton University, 1989)
Polymer films: extrusion, additive diffusion, interfacial phenomena, mass transfer modeling, polymer thermodymanics

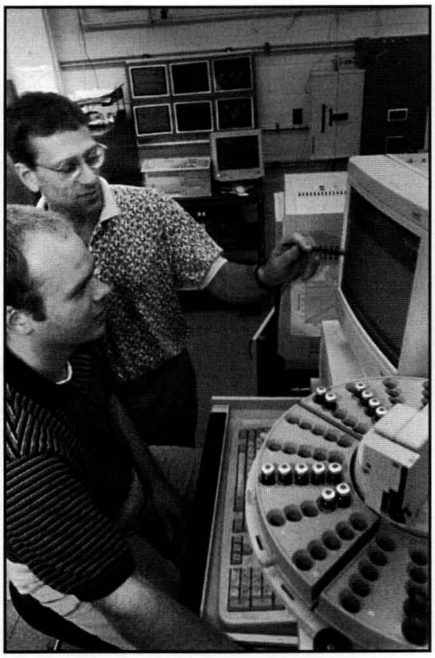
Scott Husson (PhD, University of California, Berkeley, 1998)
Bioseparations, reversible complexation in adsorption and extraction, environmentally benign processing

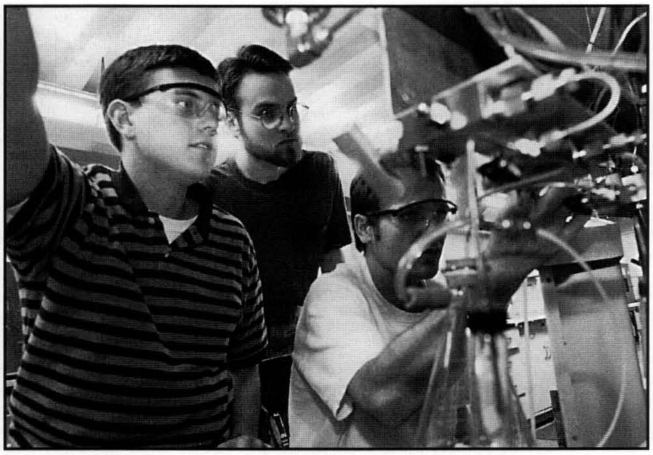
S. Michael Kilbey II (PhD, University of Minnesota, 1996)
Equilibrium and dynamic behavior of molecularly thin films, interface modification using amphiphilic molecules and electrically conductive polymers, surface forces measurements

Amod A. Ogale (PhD, University of Delaware, 1986)
Polymer processing; composite formation, characterization, micromechanics and modeling; stereolithography and rapid prototyping

Richard W. Rice (PhD, Yale University, 1972)
Kinetics and catalysis, heterogeneous catalysis in petrochemical and related reactions, catalyst characterization, environmentally related catalysis

Mark C. Thies (PhD, University of Delaware, 1985)
Thermodynamics and supercritical fluids, separation processes, materials processing, phase behavior of complex mixtures, environmental applications





Above: Experiments in Dr. Thies' lab are designed to produce phase equilibrium data, usually at high temperatures and pressures.

Left: Professors Husson and Thies discuss an on-line analytical scheme.

10 to 15% of our BS graduates elect to continue their engineering education by pursuing graduate study, and one or two each year choose law school or medical school to further their education. To ensure that students with such diverse interests and career aspirations are well prepared, the Bachelor of Science program in chemical engineering at Clemson emphasizes broad, fundamental principles in science and engineering rather than narrow specializations. Over half of Clemson's chemical engineering undergraduates also gain valuable experience, career insight, and financial assistance by participating in the Cooperative Education Program, which requires at least three semester-long work periods in industry.

The Clemson chemical engineering faculty has placed a high priority on undergraduate instruction since the formative years of the department under the leadership of Charlie Littlejohn. Traditional methods are honed and applied conscientiously, and innovations are continuously being developed and tested to better reach today's students. For example, to improve the communication skills of students, Doug Hirt uses journal writing in most of his undergraduate classes. He and Charles Barron also developed the concept of evolving design projects several years ago with support from the NSF SUCCEED coalition. In the introductory sophomore chemical engineering course, a new process flow sheet is introduced each year, and student teams are formed to study and solve material and energy balance problems. The same flow sheet follows the students through the curriculum, with new aspects being investigated in each course, such as pump specification in fluid flow and heat exchanger layout in heat and mass transfer. In the first semester of the capstone design sequence the evolving design project culminates with an economic analysis.

Doug Hirt is a frequent speaker and author on the subject of both evolving design projects and effective writing assignments in engineering education. He was honored recently by the Chemical Engineering Division of the ASEE with the 1998 Ray W. Fahien Award, which recognizes outstanding teaching effectiveness and educational scholarship. Doug also chairs the Teaching Effectiveness Committee in the College of Engineering and Science. Jim Haile was also recognized in 1998 by ASEE's Chemical Engineering Division, winning the Corcoran Award for his series of papers, "Toward Technical Understanding," which appeared in the Summer 1997, Fall 1997, and Winter 1998 issues of *Chemical Engineering Education*. In these papers Jim investigated the fundamental question of what is meant by understanding of technical material. He is now immersed in the application phase of that quest as a teacher, investigating new ways to inspire, probe, and open the minds of undergraduates as they attempt to grasp the concepts of chemical engineering.

The commitment to teaching excellence is also in good hands with the most recent additions to the chemical engineering faculty. At the May, 1999, commencement exercises, Mike Kilbey received Clemson's top teaching honor for the year, the Alumni Master Teacher Award. It is rare for a professor in one of the university's smaller departments to receive this student-determined award; even more notable, Mike is the youngest recipient ever. Though they haven't yet received such singular awards, David Bruce and Scott Husson have also demonstrated their ability to establish excellent rapport with students at all levels and to guide them to understanding the intricacies of chemical engineering.

Undergraduate students who complete Clemson's chemical engineering program develop a sense of community and pride that is nurtured by small class sizes (usually 20 to 30

In its 110-year history, Clemson University has matured from a small agricultural college to a nationally recognized, comprehensive university.

students), accessibility of the faculty, a heavy emphasis on team projects, and the professional and social activities of the AIChE student chapter. Enrichment opportunities include the Co-op Program and the Senior Departmental Honors Program through which academically qualified students can participate in research activities with the faculty and graduate students. The two-semester senior seminar series also serves to complement the classroom and laboratory experience and prepare students for entry into the profession. In the fall semester the seniors learn about career opportunities, resume preparation, interviewing, and early career success skills from a series of external speakers, including recent graduates of the department. In the spring they refine their speaking skills further and learn from each other about business aspects of the chemical industry, professional ethics, safety, the environment, and other topics researched and presented in 40-minute team seminars.

The undergraduate unit ops lab emphasizes planning and execution of experiments, analysis of results, technical communication, and teamwork.

Achievements such as the National Science Foundation's designation of the Center for Advanced Engineering Fibers and Films as an NSF Engineering Research Center hold great promise for the future.

GRADUATE OPPORTUNITIES

The Department offers advanced study leading to the Master of Science and Doctor of Philosophy degrees. The MS degree requires completion of a research thesis and 24 semester credit hours of graduate-level courses. Four core courses are required: Advanced Transport Phenomena, Chemical Engineering Thermodynamics. Chemical Engineering Kinetics, and Separation Processes. Of the remaining twelve credit hours of technical electives, at least six must be in chemical engineering. For graduate students interested in polymers, transport phenomena, or process simulation, an exciting new series of interdisciplinary courses covering chemistry, flow behavior, transport phenomena and visual simulation of polymer flow and orientation is offered through Clemson's Center for Advanced Engineering Fibers and Films.

The MS Industrial Residency Program is a special arrangement involving Clemson University, a graduate student, and a sponsoring company. Typically an MSIRP student initiates a research project at the sponsoring company's site during the summer, completes the required 24 hours of course work in the following fall and spring semesters, and then returns to the company for another seven months of full-time research. This program is restricted to U.S. citizens. Graduate residency students are paid at the prevailing salary level for BS chemical engineers for the ten months on site, but the salary is distributed over the 19-month program. This arrangement results in a monthly stipend about 40% higher than normal graduate assistantships. The sponsoring company also pays tuition and fees, and the research is conducted under joint faculty and industrial supervision and produces a thesis or an equivalent formal report. The MSIRP is an excellent program for students who want to gain industrial experience while pursuing a graduate degree, whether their ultimate intent is to continue with the PhD or to enter industry full-time after earning an MS degree.

Students in Clemson's PhD program must complete at least 36 hours of approved course work beyond the BS, including the MS course requirements (or equivalent courses taken elsewhere) and at least 12 hours in fields other than chemical engineering. PhD students plan their course work with the approval of a research adviser and advisory committee to ensure general competence in chemical engineering, a comprehensive knowledge of the field of specialization, and a mastery of research methods. Each PhD student must pass a written comprehensive exam based on undergraduate and graduate course work, and an oral comprehensive exam, which consists of the presentation and defense of a formal research proposal. After a student's research is completed, the final requirement for the PhD is the oral defense of the dissertation.

RESEARCH AREAS

The research interests of the faculty are summarized in Table 1. Strong, multifaceted programs exist in materials science and engineering, particularly polymer studies, thermodynamics and separation processes, and kinetics and catalysis. These programs encompass most of the traditional branches of chemical engineering as well as newer areas, such as advanced rheology, supercritical fluids, molecular simulation, and biotechnology. Research interests of the faculty range from purely theoretical topics to the analysis and improvement of full-scale industrial processes. Two Chemical Engineering faculty were recognized this year for their research accomplishments: Mark Thies received the McQueen Quattlebaum Faculty Achievement Award from the College of Engineering and Science, and Dan Edie received the Alumni Award for Outstanding Achievement in Research from Clemson University.

Research opportunities in the department increased exponentially in 1998 with the National Science Foundation's recognition of Clemson's Center for Advanced Engineering Fibers and Films (CAEFF) as a national Engineering Research Center. This signal event is expected to bring more than $100 million in research support to Clemson over the next ten years. "This award does more than establish us as a national research institution," said Thomas M. Keinath, Dean of Clemson's College of Engineering and Science. "It challenges Clemson to be a leader in the nation's revolution in engineering research and education. What we do in the coming years will have a profound effect on the fiber and film industry as well as the nation's next generation of engineers and scientists."

THE COLLEGE OF ENGINEERING AND SCIENCE

The Department of Chemical Engineering resides in Clemson's College of Engineering and Science (COES), the largest of the University's five colleges. Other engineering disciplines in the College include Civil, Electrical and Computer, Mechanical, Industrial, Ceramic and Materials, Biosystems (formerly Agricultural), and graduate-only programs in Bioengineering and Environmental Engineering and Science. A major reorganization of the University in 1995 also

The Center for Advanced Engineering Fibers and Films

The Center for Advanced Engineering Fibers and Films is a National Science Foundation Engineering Research Center that comprises a partnership between Clemson University and the Massachusetts Institute of Technology. The Center provides an integrated research and education environment for the systems-oriented study of fibers and films. It is the only NSF ERC in the nation to deal exclusively with fibers and films, an industry that accounts for 25% of the manufacturing segment of the U.S. gross domestic product. The industry's manufacturing base includes electronic components, fiber optic cables, synthetic fibers, multi-layer food-packaging films, and reinforced composites used in construction and aircraft. Products to be affected—in some cases, reinvented—as a result of Clemson research can be found in fields as diverse as biomedicine, transportation, communication, and construction.

Through CAEFF, faculty who are recognized for their expertise in key areas of engineering and science are partnering with fiber and film manufacturers to study polymeric fibers and films. These interdisciplinary teams are providing the knowledge base necessary to advance technology in engineering fibers and films and supporting an educational program to produce highly qualified professionals to lead this vital materials industry into the 21st century. Much of the work involves faculty members from the Chemical Engineering Department. In addition to Dan Edie, who directs CAEFF, Mark Thies, Amod Ogale, Doug Hirt, Mike Kilbey, David Bruce, and Graham Harrison are key participants. Dr. Hirt leads one of the Center's three major research thrusts. Drs. Thies, Ogale, and Kilbey head three of the Center's eight primary research topics.

Center facilities include its centralized research/teaching testbed, comprised of integrative fiber and film processing laboratories, on-line measurement instrumentation, a molecular modeling laboratory, and a virtual reality laboratory. Center researchers have access to an impressive battery of sophisticated instruments including FTIR, IR, UV, Raman and mass spectrometers; gas, liquid, gel permeation, and supercritical fluid chromatographs; thermal analysis instruments; x-ray analysis instruments, Instron capillary as well as Rheometrics and Haake rotational rheometers; and a central microscope facility. The Center also has several devices for the preparation of fiber and film precursors, small- and pilot-scale fiber and film extrusion equipment, compression and injection molding equipment for the fabrication of composites, and instruments for the physical testing of fiber, film and composite samples.

In CAEFF, chemical engineering undergraduate and graduate students join interdisciplinary research teams that are developing advanced process models capable of predicting final fiber and film properties. This work focusses on integrating molecular information into continuum models. To verify those models, CAEFF faculty, students, and industry partners are conducting an extensive experimental program for precursors ranging from conventional polymers, such as nylon and polyester, to liquid crystalline materials. The models are ultimately converted to 3-D visual process simulations. The goal is to create a new class of virtual process models that would allow fiber and film producers to develop new and improved products rapidly and efficiently. By designing materials at the molecular level, CAEFF is pioneering engineering technology for the 21st century.

In addition to undergraduate and graduate research programs, CAEFF provides short courses for industrial personnel, sponsors conferences and workshops, and pre-college outreach programs to attract younger students to engineering and science disciplines.

The National Science Foundation has committed $12 million in support for the Center in its first five years, with the total NSF funding anticipated at more than $20 million. In addition, the State of South Carolina and the University have committed $1 million per year, and industrial partners have already pledged more than $1 million per year to support the Center's research and education programs. Partnering industries include 3M, Allied Signal, Arteva Specialties, BP Amoco, Celanese Acetate, Collins and Aikman, Cryovac Division of Sealed Air Corp., Dow Chemical, DuPont, Kemet, Raytheon STX, MSNW, N.H. Andreas, and Shell Chemical.

For more information on CAEFF, visit the Center web site at
www.clemson.edu/caeff

brought the Departments of Chemistry, Computer Science, Geological Sciences, Mathematical Sciences, and Physics and Astronomy into the college as well as the School of Textiles, Fibers, and Polymer Science. Clemson also offers a comprehensive General Engineering program designed exclusively for freshman engineering students and students who transfer from one of the state's two-year institutions. This course of study provides a solid grounding in the fundamentals of engineering while the student explores the many options available in the engineering field. Upon completion of the freshman curriculum, students select their specific engineering major.

South Carolina has been very successful in cultivating international investment in business and manufacturing, with more that 500 companies representing 27 countries now located in the state. Numerous international firms, including Michelin North America and BMW Manufacturing Corporation have both national headquarters and manufacturing plants in South Carolina. Clemson University has formed academic and business partnerships with many of these firms and the countries they represent, creating study-abroad programs that give engineering and science students a strong competitive advantage.

The Engineering Program for International Careers (EPIC) prepares engineering students to be more competitive in the international arena. Key features of this program include:

- *Foreign language courses, including a summer immersion program, to provide competency in French, German, Japanese or Spanish.*
- *An International Internship to provide experience living and working in a foreign culture.*
- *EPIC graduates receive a certificate to document completion of the program.*

The College of Engineering and Science is also committed to student support. The Programs for Education Enrichment and Retention (PEER) was begun to help underrepresented students in the College of Engineering and Science. PEER students are assigned in groups to a first-year PEER mentor, who is a junior, senior, or graduate minority student of the COES. The mentor meets with the PEER group regularly to share information. The PEER office also sponsors study halls, counseling, seminars, and social events. The Program for Educational Enrichment and Retention has helped make Clemson's graduation rate of African American engineering students the 5th highest in the nation.

As female enrollment in the COES has grown over the last two decades, the College responded with WISE (Women in Science and Engineering). An outgrowth of the PEER program, WISE encourages women to persist in preparing for and obtaining careers in science and engineering and to help them be successful in those careers. Academic assistance, including mentoring, advising, tutoring, and study groups, as well as a special resource library, is sponsored through the WISE office. Wise is definitely having an impact. Although women make up only 22% of the COES undergraduate student body (30% in chemical engineering), they won over 60% of the student awards presented this year.

Computers are essential to today's electronic modes and methods of communication as well as technical calculations. For the 1998-99 and 1999-00 school years, the College of Engineering and Science is hosting a Pilot Laptop Program for undergraduates at Clemson. Students can purchase high performance laptop computers at a discount. Special laptop courses are held in classrooms equipped with ethernet connections at every desk. Courses are being offered in English, math, chemistry, computer science, physics, history, and engineering.

CLEMSON UNIVERSITY TODAY

Thomas Green Clemson's dream has become the nucleus of agricultural, scientific, and technological advancement in South Carolina. Full-time enrollment at Clemson University is now approximately 16,300 including 3,700 graduate students. Clemson offers 73 undergraduate and 70 graduate areas of study in its five academic colleges. The University is accredited by the Southern Association of Colleges and Schools to award the bachelor's, master's, specialist and doctoral degrees, and appropriate curricula are accredited by various professional organizations and associations.

Nestled in the foothills of the Blue Ridge Mountains on the shores of Lake Hartwell, Clemson offers the amenities of a small, southern town while providing big-city opportunities. The local environs provide unlimited, year-round opportunities for outdoor recreation, including whitewater rafting on the Chattooga River and watching the Tigers play nearly every sport known to mankind. The University community provides and hosts numerous cultural events, and both Atlanta, Georgia, and Charlotte, North Carolina, are just two hours away via I-85. Clemson is 50 minutes from the regional GSP airport and only a half-hour from Greenville, South Carolina, which claims the greatest number of engineers per capita in the United States.

In its 110-year history, Clemson University has matured from a small agricultural college to a nationally recognized, comprehensive university. Achievements such as the National Science Foundation's designation of the Center for Advanced Engineering Fibers and Films as an NSF Engineering Research Center hold great promise for the future. With innovative faculty, curricula, facilities, and programs that respond to the needs of students, citizens, and industry, the Department of Chemical Engineering will continue to contribute toward Clemson University's goal of preparing students for 21st century careers.

Additional information about Clemson University, the Department of Chemical Engineering, and the Center for Advanced Engineering Fibers and Films may be found at http://www.clemson.edu ❐

Carol Hall

of North Carolina State University

Richard M. Felder
North Carolina State University • Raleigh, NC 27695

If you walk into 119A Riddick Labs at North Carolina State University, the odds are you'll see two people in there, facing each other in adjacent chairs in front of the desk. One is Carol Hall, whose office it is. The other could be anyone—an undergraduate, a graduate student (who might or might not be her advisee), a postdoc (ditto), a faculty colleague, or a former advisee. The visitor could be there to talk about some subtle point of statistical thermodynamics or molecular simulation or how to get a better grade on the next test or what to do about a personal problem or just to shoot the breeze for a while. The topic doesn't matter—the visitor will have Carol's undivided attention for as long as he or she is there, and so will the next one and the one after that. You can't help but wonder how she ever manages to get anything done.

But she manages quite well. Between conversations in the past decade or two she has managed to get enough done to become a widely recognized leader in the field of molecular thermodynamics, a first-rate teacher, and the mother of three remarkably talented children. She also makes the best stuffed cabbage you ever tasted in your life.

LIFE AND TIMES

Carol Klein Hall grew up in Brooklyn, the daughter of two unusual parents. Her father was an attorney, businessman, and politician. He ran for Brooklyn borough president but lost to the machine candidate; he served as a New York City Transit Commissioner and fought (unsuccessfully) to keep the subway fare at 5¢; he organized a network of 150 trucking companies to help supply Israel in the 1948 war; and he coordinated the famous JFK birthday party at Madison Square Garden. Her mother stayed at home while Carol and her younger brother Mitchell were growing up, worked in an administrative position in the U.S. District Court in the 1970s, and then went back to get her college degree at age 63.

When Carol was 14, her parents and the parents of a boy who lived nearby decided that she and Henry would make a nice couple. He was definitely interested but she had other fish to fry and nothing came of it. He was crushed, but recovered enough to go on to a rather successful show business career, and Carol and Henry (Winkler, aka "The Fonz") have remained in touch and still enjoy each other's company whenever they have a chance to get together.

Carol gravitated into a science career at about the same time the first satellite gravitated into orbit. The national anxiety over Russian scientific supremacy triggered by Sputnik turned New York City science teachers into evangelists: if their students could handle algebra, they were encouraged to become scientists. Carol handled algebra very well, and when her high school physics teacher, Dr. Herman Gerwitz, assured her and her skeptical mother that "women could be physicists too," that was that, and off she went to become a physics major at Cornell.

There were forty physics majors in Carol's entering class at Cornell, six of them women. There were twelve left in her graduating class, of whom six were the same women. She does not speak fondly of her undergraduate educational experience, having found most of her professors remote and seemingly indifferent to the success or failure of their students. When asked how she accounts for the remarkable success of her female classmates, she replies that they recognized that the support they would need to survive would have to come from themselves, so they networked with one another to provide it, and it worked.

Carol met Tom Hall in a sophomore physics lab at Cornell,

. . . in the past decade or two [Carol] has managed to get enough done to become a widely recognized leader in the field of molecular thermodynamics, a first-rate teacher, and the mother of three remarkably talented children.

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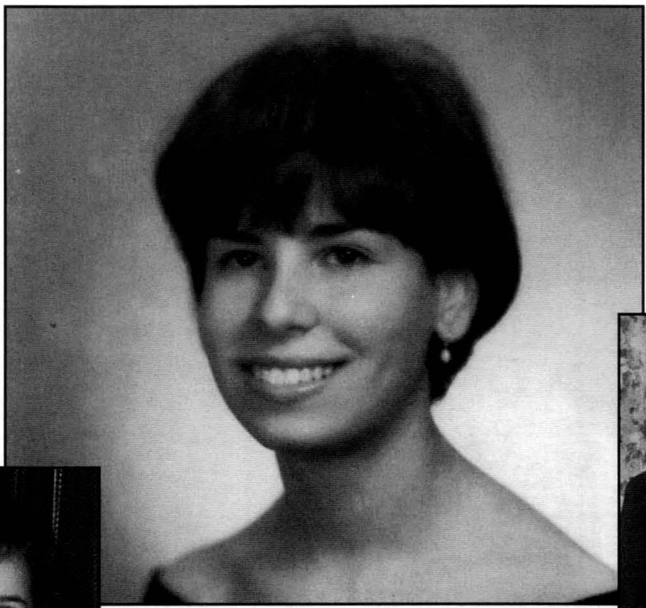


Carol at the tender age of four (below) and then, a few years later, all grown up and graduating from Cornell in 1967.

1967 also saw Carol's marriage to Tom, shown at the right with her proud parents Harris and Celia Klein.

Carol's own family, shown below, includes (bottom row) Katie (25), Norah (16), Carol; (top row) Adam (21) and Tom.

where he was an engineering physics major. They ignored each other as sophomores, noticed each other as juniors, got married as seniors, and went to graduate school together in physics at the State University of New York at Stony Brook. Carol began her doctoral program by studying critical phenomena, and as part of that project wrote her first computer program, foreshadowing the major role that computer simulation has played in her subsequent research. After a year she learned about the statistical mechanics research being carried out by a new professor named George Stell. She thought it sounded interesting, found out more about it, became intrigued by the idea that simply by knowing the forces between two molecules one could understand the collective behavior of 10^{23} of them, and switched advisors to become Stell's first Ph.D. student. The roots of her growth as a researcher were planted.

Stell was Carol's first true mentor. He communicated his passion for research and intellectual inquiry to her—sometimes in his office and sometimes at his kitchen table. He showed her how research is done and at the same time gave her the freedom and encouragement to develop her own style of approaching problems. That freedom was exactly what she needed to come into her own as a scientist. Until then she had been the typical underconfident college woman of her generation, believing that her sometimes less-than-outstanding performance in the classroom was irrefutable evidence of her lack of ability. Once she began working with Stell, she began to truly believe that Dr. Gerwitz was correct about the possibility of women being physicists. Her dissertation research was a study of how repulsive and attractive intermolecular forces compete to determine the shape of the phase diagram. She spent many happy hours attempting to "think like a molecule" and constructing questionable analogies between the behavior of systems of molecules and of mixed-gender groups.

Carol and Tom received their doctorates on the same day and at the graduation gave joint speeches about the challenges that confront two-career families. As if to illustrate their speeches, they each got job offers but none from the same place, so they went back to Cornell and Carol took an unpaid postdoctoral position in the Chemistry Department, working in the world-renowned chemical physics group led by Ben Widom and Michael Fisher. In her work with Widom, she explained why the critical-point scaling relations break down in the ideal Bose gas at greater than four dimensions. She and a postdoctoral colleague also developed lattice gas models that explained the peculiar hourglass-shaped phase diagrams observed experimentally for certain gas mixtures at high pressures. Her daughter Katie (a gifted actress, singer, and dancer now working in New York) was born during this period.

Much of Carol's career has been devoted to overcoming the obstacles to success faced by women in technical fields and then helping others overcome them. . . . she constantly tries to help others form supportive networks.

Three years later when Carol was ready to find a paid position, the notoriously bad job market of the early 1970s had commenced and there were few academic openings in physics to be found. She and Tom considered themselves fortunate to land jobs together at Bell Laboratories, working on the applied technology side of the house. She worked in the economic modeling department, combining her knowledge of probability theory with her native New Yorker's instinct for competitive shopping to produce an innovative model for pricing multiple products that competed with one another.

Although Carol enjoyed her work at Bell, she wanted to get back into real science. The head of the Chemical Engineering Department at Princeton University at the time was Leon Lapidus, a visionary who believed that women would be valuable additions to the ranks of chemical engineering faculties. Since there were only two female chemical engineering professors in the entire country at the time and hardly any in the graduate student pipeline, Lapidus decided to recruit from closely related disciplines. He invited Carol to consider a career change, a chance at which she jumped. Sadly, Lapidus died suddenly a month before she came on board.

The move from physics to chemical engineering proved to be a major cultural shift, and forced her to re-evaluate her position on the continuum between "rigorous" and "close enough." She was bemused, for example, by the notion that the number of theoretical stages in a separation process often depended on how sharp your pencil was. She eventually negotiated the transition, however—she learned the jargon, got the grants, performed widely recognized research into the phase behavior of metal hydrides, and won the Rheinstein Outstanding Young Faculty Award. She also became a popular teacher, teaching courses she had never taken. She discovered that chemical engineering was a veritable gold mine of intellectual challenges, offering many exciting research problems that were ideally suited to approaches grounded in statistical thermodynamics. Her son Adam (now a student of art and history at Tulane) and daughter Norah (a talented and—as Katie was—stage-struck high school student) were born during her Princeton years.

In 1985 Carol became the latest in a distinguished line of New Yorkers who made the transition from thinking "North Carolina—isn't that south of Jersey somewhere" to joining the Chemical Engineering Department at North Carolina State University. At N.C. State her career has flourished. She has made ground-breaking advances in the modeling of polymer structures, trained 21 graduate students and 5 postdoctoral fellows, published over 125 papers in the most prestigious chemical engineering and physics journals in the world, and won the NCSU Alumni Association Outstanding Research Award and the Alcoa Foundation Distinguished Engineering Research Award.

RESEARCH

Carol's research on metal hydrides at Princeton was motivated in part by the energy crises of the early 1970s. Skyrocketing gasoline prices had led many people to look to hydrogen as a clean alternative fuel, and metal hydrides were strong candidates as hydrogen storage media. Carol performed Monte Carlo simulations on lattice models of metal hydrides and successfully explained the unusual phase behavior that accounted for the metals' ability to absorb vast quantities of hydrogen. At the same time, a team composed of Carol, Princeton colleague Bill Russell, and Ph.D. student Alice Gast (now a professor at Stanford) used perturbation theory to explain the phase behavior that underlies polymer-

Princeton faculty and graduate students in 1978 included a very pregnant (8 months) Carol (first row, next to last).

Interested readers may also spot other familiar (youthful) faces in the first row (left to right): Bob Bratzler; Mort Kostin; Dick Toner; Ernie Johnson; Ron Andres, with Bill Russel peeking from behind him; Carol, with Bob Axtman behind her and Dudley Saville behind Bob; and Joe Calo, with Dave Ollis behind him to the right and Bob Prud'homme behind him to the left.

induced colloidal precipitation. Their research demonstrated that such systems can coexist in three phases analogous to gas, liquid, and solid, a phenomenon that had been observed experimentally in the preceding year. While doing all that and having two babies and co-running a home, Carol still found time to collaborate with Gene Helfand of Bell Laboratories to develop a model for conformational state relaxation in polymers. The result was the so-called Hall-Helfand correlation function, which has become a standard against which to compare results of NMR relaxation and time-resolved fluorescence spectroscopy experiments.

Towards the end of her time at Princeton, Carol became interested in fluids containing what she calls "chainlike" molecules, a subject that has become her main area of interest at North Carolina State. For the past half-century, the state of the art in polymer modeling has been the classical work of Flory and Huggins, which is based on a model of chain molecules confined to a lattice. While revolutionary for its time, the Flory-Huggins model has a number of shortcomings, not least of which is that the so-called Flory parameter—which the model presumes constant—turns out to depend on variables such as composition, polymer chain length, and temperature.

In the mid-1980s Carol and her coworkers identified intrinsic differences between chains moving on a lattice and chains moving in continuous space as the principal limitation in the predictive capability of the Flory-Huggins theory. By blending the probabilistic reasoning underlying the original Flory approach with powerful theories of liquid-state physics that had previously only been applied to monatomic and diatomic fluids, they developed the "Generalized Flory Theory," providing an elegant and deceptively simple approach to constructing equations of state for mixtures of fluids and polymer molecules made up of segments of different size, shape, energetics, and angular constraints. The theory is computationally convenient and physically intuitive, and has been found to be remarkably accurate in extensive tests against computer simulation data. Carol's papers in this area have stimulated a flurry of follow-on research in the chemical engineering thermodynamics community.

Carol's contributions also include trailblazing simulations of the dynamics of entangled polymer melts. Her molecular simulations are considered computational tours de force, spanning almost six orders of magnitude in time. They are aimed at reconciling the two competing theories of polymer entanglements: the older view that polymer chains entwine to form a so-called "local knot" and the more recent view that chains "reptate" through a tube formed of surrounding molecules. The simulations show that both types of entanglements influence polymer dynamics, but that they occur on different time scales.

Carol's latest venture is into the area of protein aggregation, a phenomenon associated with (and possibly a cause of) many degenerative diseases such as Alzheimer's, Huntington's, and "mad cow" disease. She and her students recently completed the first computer simulation of the simultaneous aggregation and folding of model proteins. One of their major findings is that a crowded protein environment can distort the folding pathway, making it more likely that pathological partially folded intermediates will be stabilized and will then aggregate. Such "misassembly processes" are hypothesized to be the catalyzing events for fibril formation, the physical manifestation of Alzheimer's disease.

Carol's work has gained considerable attention throughout the scientific community. As of the writing of this article, her papers have been cited 2500 times, and five of them have been cited more than 140 times each. Her accomplishments and widespread recognition led to her designation as Alcoa Professor of Chemical Engineering at N.C. State.

TEACHING, SERVICE, AND MENTORSHIP

Carol enjoys a reputation as an excellent undergraduate teacher. Recalling the impersonal nature of her undergraduate instruction and the difficulties it caused many of the students, she makes a point of learning every student's name, no matter how large the class. In her writing and lecturing, she takes great pains to make the complex seem simple and yet manages to leave her students with a deep understanding of the physical ideas that underlie the formulas and algorithms she presents. Long before "Writing Across the Curriculum" became a buzzword in educational circles, she recognized that the exercise of writing frequently leads to improved clarity and depth of thinking, and she has become locally famous for requiring the students in her thermodynamics courses to write essays on concepts that have baffled generations of engineering students. Remarkably, she reads and provides feedback on every essay, even though class sizes at N.C. State sometimes approach 100.

The insights Carol has acquired in several decades of teaching thermodynamics will be reflected in an undergraduate textbook scheduled to be published in 2000 by Oxford University Press. The book's aims are to introduce the idea that thermodynamic properties are a direct reflection of molecular size and shape and the nature of the interactions among neighboring molecules; to illustrate thermodynamics concepts with up-to-date examples that go beyond the usual ones involving light hydrocarbons; and to help students formulate a general strategy for setting up and solving most thermodynamics problems.

A variety of professional service activities augment Carol's career dossier. She has organized numerous sessions at professional society meetings, initiated a reception for women chemical engineers that has become a fixture of the annual AIChE meeting, and is currently the consulting editor for thermodynamics of the AIChE Journal. She serves on the Executive Board of the National Programming Committee and on the AIChE ABET Accreditation Team, and is on the editorial boards of Molecular Physics and the Journal of Chemical and Engineering Data.

Mentorship is at the heart of Carol's professional activities. Those constant conversations with graduate students in Carol's office are not just incidental to her job—she considers them the most important part of it. In putting together an award nomination package, the Chemical Engineering Department recently asked some current students and former advisees to reflect on the impact she had on their professional and personal lives. Their comments paint a remarkable portrait of a truly gifted role model to young people. For example, "Dr. Hall is a special person to many graduate students, not just her own." "I can only hope that I will touch people's lives the way that Dr. Hall has." "I believe she is genuinely interested in what I am going to become, not just in my research results." "I [and indeed, all students who interact with her] owe a great deal to her active interest in our intellectual and personal growth, which is supplemented by her terrific sense of humor, patience, much wisdom, and undoubted scientific expertise."

Former advisee Professor Alice Gast wrote "Everyone should have a list of the most influential people in their lives. Carol is near the top of my list." Dr. Kevin Honnell of Los Alamos National Labs wrote "As we began to work together, what impressed me much more than the research itself was the quality of the training Carol provides to her students and the exceptional care and commitment she invests in their intellectual, social, and emotional well-being." Dr. Mauricio Futran, recently promoted to Executive Director of Chemical Process Development at Bristol-Myers Squibb, commented, "Her support, encouragement, and advice do not stop at graduation. It is typical for her students to stay closely in touch and to rely on her feedback through the years, both on professional and personal matters." George Stell has a right to feel proud of his first PhD student and of himself. Good mentoring bears rich fruit.

Attracting and retaining women has widely been recognized as an important challenge facing science and engineering education. Much of Carol's career has been devoted to overcoming the obstacles to success faced by women in technical fields and then helping others overcome them. She learned the value of networking and mutual support as an undergraduate at Cornell, as one of a handful of female graduate students in physics at Stony Brook, and as the only female engineering faculty member at Princeton, and she constantly tries to help others form supportive networks.

When speaking to women students in her office and at seminars, Carol offers insights based on her experience. She tells her listeners about the research showing a drop in confidence experienced by many women in science and engineering, both in school and in the workplace. She encourages them to join forces and provide one another with the kind of mutual support that helped her survive professionally, and she gives them a modified version of the Herman Gerwitz message, assuring them that women can indeed succeed in engineering. No one is better qualified to deliver this message. ❐

ChE letter to the editor

Dear Editor:

Ten years ago, Sanders and Sommerfeld[1] published an interesting article presenting a laboratory experiment on combined mass transfer and kinetics. Specifically, the increase of the pH in an aqueous solution of acetic acid was followed with a digital pH-meter during neutralization with commercial antacid tablets. This experiment was selected mainly because its cost is very low and because it allows an interesting process to be studied.

Since approximately 1989, we have implemented this experiment in our undergraduate laboratory on mass transfer and kinetics, following all the instructions, including the experimental system, procedure, theory, and the data analysis, as presented in the above-mentioned paper.

Nevertheless, a closer study of the discussion presented by these authors revealed important inconsistencies that cannot be obviated, and the argument of the authors that the model provides a good fitting of the pH (though the constants reported are not correct) involving a very simple data reduction procedure seems to be not acceptable.

The authors represent the system by a very simple overall reaction:

$$2\,H_3O^+ + CO_3^{2-} \rightarrow 3\,H_2O + CO_2$$

and they assume that the instantaneous rate, measured as the rate of disappearance of the hydronium ion, is proportional to the remaining surface area, a, of the tablets and the hydronium ion concentration, with the order of the latter as yet unspecified.

Nevertheless, the fact that the material balances and the equilibrium between the acetic acid and the acetate, as well as the dissolved CO_2 were not considered in their model, would lead to the nonsense conclusion that the $CaCO_3$ and acetic acid are almost not consumed during the experiment reported, which is, obviously, contrary to reality.

According to the previous considerations, we suggest to our students the following model to explain the dissolution (and neutralization) of antacid tablets:

1. *Reactions involved:*

$$2\,H_3O^+ + CaCO_3 \xrightarrow{k_1} CO_2 \uparrow + 3\,H_2O + Ca^{2+}$$

$$H_2CO_3{}^* + CaCO_3 \xrightarrow{k_2} Ca^{2+} + 2\,HCO_3^-$$

2. *The pH of the solution and the acid concentration are the result of the equilibrium of the non-reacted acetic acid, the acetate anion (formed as a consequence of the reaction between the acetic acid and the $CaCO_3$ of the tablet), and the carbonic acid, which is in equilibrium with the carbon dioxide of the surrounding atmosphere and the bicarbonate anion. The concentration of these species are related by the corresponding chemical equilibrium, and the acid dissociation of the HCO_3^- can be neglected, since the pH of the reaction medium is, during all the experiment, low enough so as to assure the practical absence of $CO_3^{=}$ anions. To calculate the instantaneous ratio of the tablet, we use the same equation, shown by Sander and Sommerfeld.*

3. *We represent the rate of dissolution by the rate of disappearance of calcium carbonate (dN_B/dt), and obviously*

$$\frac{1}{V}\frac{dN_B}{dt} = \frac{1}{2}\frac{d\left[H_3O^+\right]}{dt} = -k_1 a^{n_1}\left[H_3O^+\right]^{n_2} - k_2 a^{n_3}\left[H_2CO_3^*\right]^{n_4} = -k_1 a^{n_1}\left[H_3O^+\right]^{n_2} - k_2' a^{n}$$

where

$$k_2' = k_2\left[H_2CO_3^*\right]^{n_4}$$

and can be considered as constant, since the concentration of dissolved carbonic acid has been considered as constant.

In order to estimate the validity of the model, the previous equation must be numerically integrated in combination with the equations corresponding to the equilibrium of the acetic and carbonic acids, which requires the knowledge of the concentration of all the species involved at any time. To solve this problem, we use the charge balance and the material balance for the acetic acid and the acetate. We have implemented several improvements to the model in order to obtain a better fit, and only the consideration of a time delay in the response of the pH meter produces a significant improvement of the fitting.

Nevertheless, the main objective of this letter is to bring attention to the type of models in our undergraduate laboratories; excessive simplifications can only be appropriate when the simplified model is able to explain adequately the whole experiment. In this case, a very simple model was applied, but was incapable of explaining the concentration variations of the different chemical species with time. On the other hand, the increasing knowledge of our students about different computer tools permits application to more complex models, with more complex equations, while keeping the time for data reduction and analysis—thus allowing teachers to emphasize the importance of developing better and more complete models.

Sincerely:

Antonio Marcilla, Maribel Beltrán, Amparo Gómez

Universidad de Alicante
Apdo. de correos n° 99
03080 Alicante, Spain

1. Sanders, A.A., and J.T. Sommerfeld, "A Laboratory Experiment on Combined Mass Transfer and Kinetics," *Chem. Eng. Ed.*, **23**(2), 86 (1989) ❒

INTRODUCING STUDENTS TO BASIC ChE CONCEPTS

Four Simple Experiments

DUNCAN M. FRASER
University of Cape Town • Rondebosch, Western Cape, 7701 South Africa

This paper describes the part played by four simple experiments in a new approach to introducing students to chemical engineering. Instead of the traditional introduction through a course in material and energy balances in the second year of study, a first-year course was introduced in 1995 in which students are exposed to some of the basic concepts in chemical engineering. This course was part of a major revamping of our curriculum aimed at reducing the overload on students, facilitating the transfer of knowledge from science to engineering, providing a better grasp of physical phenomena, and improving the motivation of freshmen.[1] The course runs for the full academic year, with half of it being the introduction to chemical engineering (taught by the author) and the other half modeling and computing (taught by staff from the mathematics department). The two halves run in parallel throughout the year.

The paper will describe the introduction to chemical engineering part of the course, with particular reference to the role played by the experiments, the objectives of the experiments, how they were developed, implementation issues, an evaluation against the objectives, how two of them are modeled, and finally a brief evaluation of the experiments in the context of the course.

THE INTRODUCTORY COURSE

The course starts developing the concepts needed as a basis for the study of chemical engineering. After much grappling to identify the essential core of what makes up chemical engineering, I came to the conclusion that we function at three different levels:

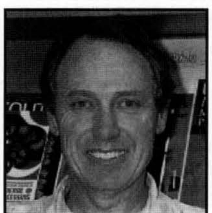
- *At the one extreme, the first level is the systems level, in which overall structures and inter-relationships between components of systems are considered.*
- *At the other extreme, the third level is the micro level of the fundamental processes occurring in the systems we work with. Again, after reflection, it was clear that there are essentially only four such fundamental processes, which occur on their own or in combination depending on the system: mass transfer, heat transfer, momentum transfer, and reaction kinetics.*
- *In between these two levels is the second level, in which we design the equipment in which these fundamental processes occur. Here we need to make use of empirical correlations because it is not possible to predict exactly what will happen theoretically.*

In this course I therefore sought to cover all three levels in a way that would help students develop these concepts as far as possible, given that they are just starting their university studies.

The first level is handled by dealing with the structure of chemical processes and showing how this is implemented in practice for some particular processes. The course starts with the manufacture of ammonia as the first example. Two visits to chemical plants (an ammonia factory and a margarine/soap factory) help to consolidate this in addition to exposing students to industrial equipment.

The students are given a number of designs to do that expose them both to the design process and to the use of correlations as part of that process, which caters to the second level. The first design is a straightforward design of a cake factory. The second design is the sizing of an absorber

Duncan Fraser *has been lecturing at UCT since 1979. He holds the degrees of BSc and PhD, both from UCT. He has taught a wide range of courses from first year to fourth year, including mass and energy balances, thermodynamics, transport phenomena, solid-fluid operations, optimization, process control, and design. His primary research interests are in engineering education and process synthesis.*



that involves setting up three equations for its solution and the calculation of diffusivities in both gas and liquid phases using correlations. This problem is specifically given to help students experience the sort of technical problems they will face in chemical engineering. The third design is part of a project on open-ended problem solving and deals with improving the energy recovery system on a plant.

The third level receives the most extensive coverage. First, at the start of the course, students are introduced to this level by discussing what happens in particular sections of the ammonia process (such as the catalytic ammonia reactor and the carbon dioxide absorber) at a micro level. The process of diffusion, which they know from physics, is used as a platform to introduce the concept of mass transfer and also the basic equation for transfer processes

$$\text{(Transfer rate per unit area)} = \text{(driving force)/(resistance)} \quad (1)$$

They are subsequently introduced to heat transfer and, toward the end of the course, briefly to momentum transfer and the analogy between momentum, heat, and mass transfer.

The four experiments were designed to give the students hands-on experience with the four fundamental phenomena. They are run toward the end of the first semester. Subsequently, at the start of the second semester (when the students have just learned differential equations in mathematics), the experiments are modeled using a shell-balance approach, and the solutions of the models are fitted to the experimental data.

The course also aims to begin developing the basic skills needed in chemical engineering. One of these is unit conversion, which students must master to pass the course. Another is modeling, which is covered in both parts of the course. The modeling of the experiments is important in this regard. It also has a key role in creating links with science and helping students to transfer knowledge from science to engineering.

OBJECTIVES OF THE EXPERIMENTS

In framing the objectives for these experiments, I was guided by the principles of fun, simplicity, quickness, and low cost as espoused by chemical engineering educators in recent years.[2-7] The objectives of the experiments were:

1. *To introduce students to the four fundamental processes of chemical engineering given above.*
2. *To provide hands-on exposure to these processes in a way that would help subsequent development of theoretical understanding.*
3. *To move students from the known to the unknown, using familiar equipment and concepts to introduce them to unfamiliar engineering equipment and concepts.*
4. *To be fun to perform, giving students a sense of the enjoyment of doing chemical engineering.*
5. *To be performed within a limited time by first-year engineering students who are not familiar with experimental procedures.*
6. *To be performed by the large number of students in the course within a few weeks, so that all students have had exposure to them by the time the modeling is to be undertaken.*
7. *To be inherently safe, given the inexperience of the students, and not use materials or procedures that could be harmful.*
8. *To not be too costly (multiple sets of apparatus being needed).*
9. *To be easily assembled because of the short time available for building the rigs and the pressure on the departmental workshop.*
10. *To use robust equipment, so as to withstand the treatment likely to be meted out by inexperienced students.*
11. *To be readily stored away so they do not occupy laboratory space for the large proportion of the year during which they are not used.*
12. *To be easily transported, so they can readily be used by other institutions within the Western Cape region in which the University of Cape Town is situated.*

There were 160 students in the course the first time it was conducted—we decided to group them in pairs for the experiments. Two afternoons of three hours duration were available each week. This meant that, if each experiment could be performed within an hour and a half, then two experiments could be done each afternoon. In order for all the pairs to be able to perform each of four experiments (one for each of the fundamental processes), five sets of apparatus were required so they could all be done in four weeks. This then set the time limit for each experiment at one-and-a-half hours. This meant that measurements had to be made on the spot—lengthy analytical procedures were excluded.

DEVELOPING THE EXPERIMENTS

The process by which each of the experiments was developed will be described in turn. This is to illustrate the serendipitous nature of such a creative exercise and to encourage others to try something similar.

Heat Transfer: Coffee Cup Cooling

This experiment arose out of a class discussion concerning heat transfer and the effect of lowering the driving force for cooling a hot cup of coffee by adding cold milk; some students felt that the increase in contact area would offset the decrease in driving force. It is, of course, a classical example.[8,9]

The students are asked to determine: if you want a cup of coffee to be as hot as possible after five minutes, is it better to put the milk in immediately or at the end of the five minutes? The rate of cooling of the coffee is determined by measuring the temperature using a hand-held digital thermometer. Measurements are made on coffee with and without milk, and also with the cup covered and/or exposed to a fan. The students are also encouraged to drink the coffee

As an adjunct to this experiment, they are also asked to perform two heat balances on a kettle while it is heating up from cold to the boiling point and while it boils for five minutes. A digital wattmeter is used for measuring the power input to the kettle and a digital scale for weighing.

Mass Transfer: Dissolution of Suckers

The germ of the idea for this experiment came from Sensel and Myers.[10] They dissolved particles of sourball candy in an agitated system and then dried and weighed them to work out the rate of dissolution. In order to model the dissolution and to make for easier measurements, I thought of using a round sweet that could be suspended in water. The answer to this came when I was out with my daughters, buying some of the equipment for these experiments. They bought some round suckers on sticks. When we got home I suddenly realized that this was exactly what I needed! I immediately placed one in some cold water to see how long it would take to dissolve. In twenty minutes it shrank from a diameter of 25 mm to 15 mm, which was just the right time scale. It was not too fast for accurate measurements of the diameter to be taken, but it was fast enough to allow testing of other conditions as well, such as stirring or the effect of warm water (all of which would increase the rate of dissolution), within the total time available.

The experiment was formulated accordingly. Magnetic stirrers were used for stirring and vernier calipers for measuring diameter. As it happened, these suckers had sherbet cores, so there was no point in dissolving them too far. The students were therefore instructed to go ahead and eat them when they reached a certain size!

Reaction Kinetics: Cooking Potatoes

This was the one I struggled with the most. How could I find a reaction that the students could see happening right before their eyes? Then, I read the comment "Consider baking a potato" at the end of the paper on model development by Barton,[8] and I suddenly remembered a demonstration that one of my colleagues, Geoff Hansford, had done for school children: he had cooked potatoes for different lengths of time, cutting them open to reveal how far the cooking had progressed. This suited my purpose ideally.

The students are given three sets of potatoes (small, medium, and large) and are given different lengths of time for cooking each of them. A vernier caliper is used to measure the diameter of the whole potato and the uncooked portion (the interface between the cooked and uncooked potato is very distinct).

Momentum Transfer: Fluid Flow through Thin Tubing

I felt that momentum transfer is the most difficult of these four concepts, so I did not use the term with the students, simply referring to it as a fluid flow experiment. I wanted the students to experience the pressure that is needed to make a fluid flow through a pipe. I set up a series of pipes (thin tubes, actually). The fluids were chosen for their wide range of viscosities: water (1 cP), ethyl alcohol (1,2 cP), isopropyl alcohol (2,23 cP), a 50% water-glycerol mixture (6,3 cP), and ethylene glycol (23 cP). The density range is not as high as I would have liked, from 789 to 1130 kg/m^3 (bearing in mind that in laminar flow the pressure drop for flow through a pipe is independent of density).

For each fluid there were three tubes of nominal size 1/4", 3/16", and 1/8". A large medical syringe of 60-ml capacity was used to suck the fluid from a reservoir into the tube and then to force it out again. A tee-piece was used to join the syringe, a pressure gauge, and the tube. The students had to time the discharge of a certain volume through the tube and measure the pressure for this flow. This was used to verify the Hagen-Poiseuille law ($\Delta P = 32\,\mu L v / d^2$, where μ is viscosity, L is pipe length, v is fluid velocity, and d is pipe diameter).

IMPLEMENTATION ISSUES

The equipment for these experiments was all purchased and assembled within a fortnight. The apparatus worked well, as would have been anticipated, apart from leaks in the tee-pieces of the fluid-flow rigs.

One problem encountered was with the pressure gauges. The ones originally used were only meant for positive pressures, and this meant that they were damaged when sucking the fluid into the syringes, especially in the lines with the thin tubes and the higher viscosity fluids. The gauges were therefore all replaced by pressure-vacuum gauges.

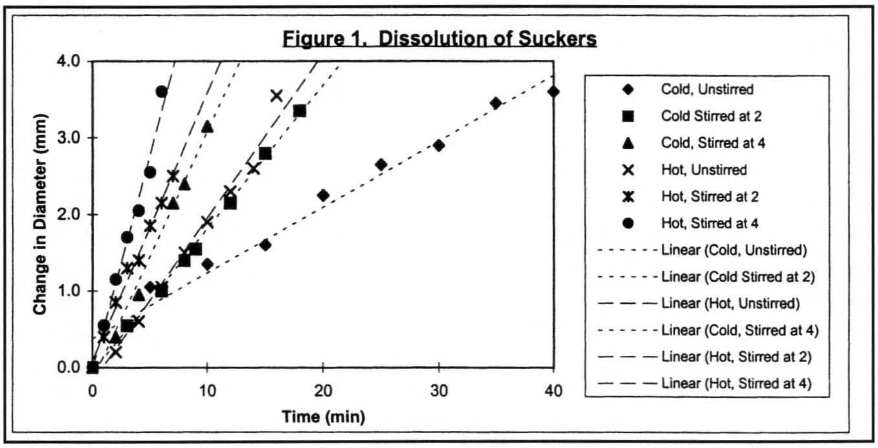
In this experiment you also have to be careful not to overpressurize the system or the flexible tubing connecting the syringe to the tee-piece comes off the end of the syringe, which is slightly conical. Another problem arose with the heated stirrers—any sugar solution spilled on them tended to carbonize, so they have to be cleaned carefully each time they are used.

EVALUATION OF EXPERIMENTS AGAINST OBJECTIVES

The experiments will now be evaluated against each of the objectives listed earlier.

1. They introduced students to each of the four fundamental processes.
2. They provided hands-on exposure to the processes. Students at the end of their studies rated them on average as 4.1 on a scale of 1 to 5 in terms of helpfulness.
3. The experiments used familiar equipment and concepts (coffee cups, kettles, a fan, cooling, suckers, dissolution, potatoes, pots, hot plates, cooking, syringes, water, ethyl alcohol, antifreeze, flow) as well as unfamiliar equipment and concepts (digital thermometers and wattmeters, heat transfer, vernier calipers, magnetic stirrers, mass transfer, reaction kinetics, pressure gauges, metal tubes, isopropyl alcohol,

glycerol).
4. Students appeared to enjoy doing the experiments and tackled them with great enthusiasm.
5. Each of the experiments was readily completed in one-and-a-half hours by a pair of students.
6. A class of 160 was able to perform the experiments in four sessions of one-and-a-half hours per week over four weeks.
7. The experiments were all safe, apart from the boiling kettle, which is no more dangerous than what is done routinely in the home and was used to bring home the danger of live steam. The fluids were specifically chosen with safety in mind—all are in common use and are safe unless ingested in large quantities.
8. Five sets of equipment for all the experiments were purchased for roughly $6,000.



9. The equipment was all purchased and assembled within two weeks.
10. The equipment has lasted well. The only problems have been failure of the digital thermometers and wattmeters (care also had to be taken to remove the batteries of these items between use).
11. Five sets of apparatus were able to be stored in five standard laboratory cupboards.
12. The equipment is readily transported and has been used by other institutions in the area.

Clearly, all of the objectives were met. The timing was also amazing—without planning it, earlier in the week in which we started the experiments the students were taught how to read a vernier scale in physics. Students also commented that the fluid flow experiment helped them to appreciate the Bernoulli equation taught in physics.

MODELING OF EXPERIMENTS

A number of important features of the experiments are exploited in discussion of the modeling. The first of these is the importance of physical observations. For example, in still water the bottom of the sucker dissolves away more rapidly than the top. Close observation reveals that there is a downward convection current of concentrated sugar solution below the sucker. This does not appear to affect the top half of the sucker, so it is still valid to assume diffusion in modeling the dissolution.

Another aspect is the variability of real systems. The suckers are neither completely round nor all exactly the same size. The potatoes are certainly not all the same shape, and within each size class there is also considerable size variation. Some potatoes are also non-uniform inside.

The data for these experiments also brings out the importance of how a problem is represented for meaningful interpretations to be made. In both the sucker and potato experiments it is not helpful to look at the final radius when making comparisons when the initial radii are different. As soon as the data is presented as differences in radii, however, clear trends emerge.

In the following paragraphs I will deal with the modeling of the sucker dissolution and the potato cooking. I am able to start this section of the course shortly after the students have been taught differential equations in mathematics, thus providing motivation for the mathematics they are being taught by showing that it is needed in chemical engineering.

Sucker Dissolution

This is modeled as diffusion of dissolved sugar from the surface of the sucker into the surrounding water. The rate of diffusion into the water is equated to the rate of shrinkage of the sucker. It is assumed that the bulk concentration of the sugar in the water does not change significantly. This yields the following straightforward differential equation in which the rate of change of radius with time is a negative constant:

$$\frac{dr}{dt} = -\left(\frac{k\Delta C}{\rho_s}\right) \tag{2}$$

where k is the mass transfer coefficient, ΔC is the concentration difference between the surface of the sucker and the bulk water, and ρ_s is the density of the sucker.

Solution of this differential equation gives a linear decrease of sucker radius with time, provided the term in the brackets is constant (the only variable in this term that will change with time is ΔC, but on checking the change is minimal and may be neglected):

$$r_i - r = \left(\frac{k\Delta C}{\rho_s}\right)t \tag{3}$$

Figure 1 shows the fitting of this model to six sets of experimental data, obtained at two different temperatures and three different stirrer speeds. The slope of the straight line includes two sets of variables, one being k, the mass transfer coefficient (which is a function of the rate of stirring), and the other ($\Delta C / \rho_s$), the concentration difference

Given that there are six sets of data, we can use the slopes fitted to the experimental data to solve for the unknown values of k and ($\Delta C / \rho_s$) by regression, as shown in Table 1. The absolute values of the variables are not important, but we can draw conclusions from their relative values. The mass transfer coefficient, as expected, is a nonlinear function of stirrer speed and the major variable in the other group, the equilibrium concentration of sugar, approximately doubles from the cold to the warm water.

Potato Cooking

In order to model this situation, a number of simplifying assumptions have to be made. The first is that the potatoes can be taken to be spherical. The next is that the rate of cooking is determined by the rate at which heat arrives at the cooking interface. This is used in conjunction with the assumption that all the heat transferred to the interface is used for the cooking reaction (this is based on the heat of reaction being much larger than sensible heat effects). I also assume that the driving force for heat transfer is constant—measurements of the temperatures of the outside of the potato and the cooking interface show that they stay constant at 98°C and 65°C, respectively (these measurements were suggested by my twelve-year-old daughter!).

In developing the differential equation for this system, you need an expression for conduction through a spherical shell. This is readily derived as part of the analysis. This, plus all the assumptions mentioned above, leads to a differential equation that is a function of the outside radius and the radius of uncooked potato at any particular time:

$$\frac{dr_I}{dt} = \left(\frac{4\,\pi k M \Delta T}{\Delta H_R \rho} \right) \left(\frac{1}{r_i^2 \left(\frac{1}{r_0} - \frac{1}{r_i} \right)} \right) \tag{4}$$

where r_o is the outer potato diameter, r_i is the radius of the uncooked potato, k is the potato thermal conductivity, M is the potato molar mass, ΔH_R is the potato molar heat of reaction, ρ is the potato density, and ΔT is the temperature difference between the outside of the potato and the cooking zone.

This equation is readily solved analytically, giving a cubic relation between the uncooked radius and time:

$$\left(\frac{1}{3\, r_0} \right) r_i^3 - \frac{1}{2} r_i^2 + \frac{1}{6} r_o^2 - \left[\frac{4\,\pi k M \Delta T}{\Delta H_R \rho} \right] t = 0 \tag{5}$$

If the assumptions are valid, then the term in the square bracket would be constant. This equation is therefore solved for this term and it is evaluated from the experimental data for the outside and interface radii at different times. The results are shown in Table 2, and this term is found to be about the same for all points, except for the single data point at one minute and the longest time for each size. This justifies the use of the assumptions made, over all but the initial and final phases of the experiments.

Figure 2 shows the resulting analytical solution compared with the actual data. As one would expect, only the points in Table 2 that

TABLE 1
Constants for Sucker Dissolution

Stirring:	*none*	*speed 2*	*speed 4*
K	0.101	0.175	0.287
Temp:	*15°C*	*37°C*	-
$(\Delta C / \rho_s)$	1.091	1.978	-

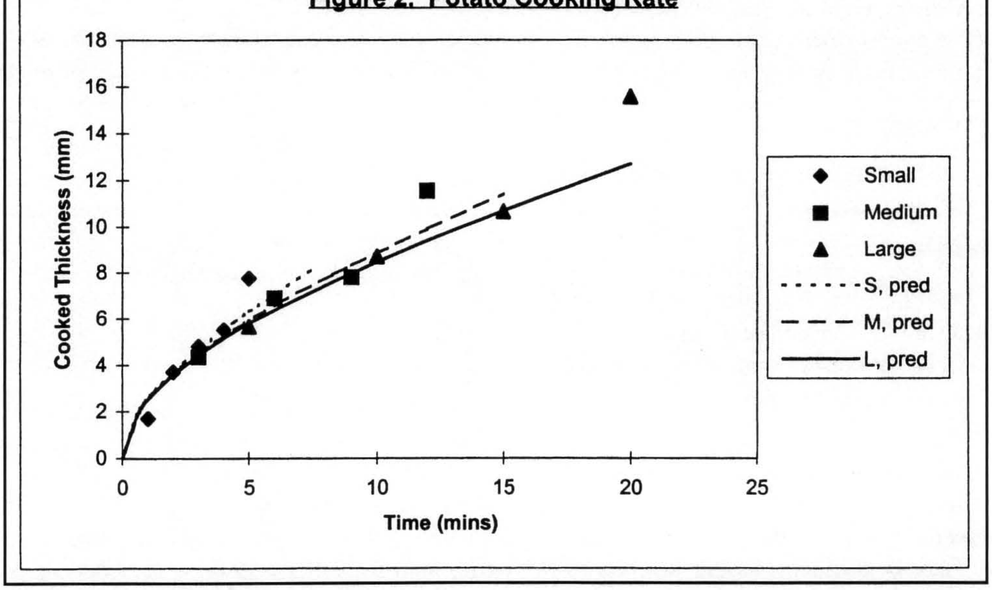


Figure 2. Potato Cooking Rate

were out of line do not match the predictions. The deviation for the last data point in each size is probably due to the assumption of a constant temperature at the cooking interface breaking down as the center of the potato is reached.

This exercise illustrates how one can derive a model on the basis of a fairly gross simplification of a situation, and also use it to make meaningful predictions, even though one cannot directly measure the characteristics of the process, such as the heat of reaction of the potato.

EVALUATION OF EXPERIMENTS

The course as a whole was evaluated by questioning students in the second year and the fourth year. A free-form questionnaire was used in both instances. In the second evaluation, students were also asked to rate each of the main aspects of the course. These two methods were used to obtain both what had left an impression on the students and the relative value they perceived in all the aspects of the course.

When asked to give the most useful features of the course, roughly two-thirds of them mentioned unit conversion (69% after one year and 64% after three years). In addition, the experiments were mentioned by 31% after one year and 56% after three years (this increase seems significant). In both evaluations, no other topic came close to these. In the first instance, they were also asked to mention the most confusing aspect of the course, and 16% felt the experiments had been confusing.

TABLE 2
Evaluation of Constant Term for Potato Experiment

Size	*Time (min)*	*Cooked Thickness (mm)*	*Constant Term*
Small	1	1.70	5.33
	2	3.70	11.60
	3	4.80	12.16
	4	5.50	11.94
	5	7.75	17.37
Medium	3	4.35	11.08
	6	6.90	12.90
	9	7.80	10.25
	12	11.55	15.06
Large	5	5.65	11.13
	10	8.70	12.54
	15	10.65	11.89
	20	15.55	15.89
Average (of values between 10 and 13)			*11.72*

The overall helpfulness of the course was rated as 3.0 on a scale of 1 to 5 after one year, and 3.5 after three years. After three years, the two highest ratings of course components were unit conversion (4.9) and the experiments (4.1), followed by transfer processes (3.9), plant visits (3.9), and the modeling of the experiments (3.8).

Unit conversion and the experiments (plus the related modeling and transfer processes) were consistently the most significant aspects of the course for the students. The increased rating of the experiments after three years points to the long-term impact that they had.

CONCLUSIONS

The experiments described in this paper perform the crucial role of introducing first-year students to four key fundamental physical phenomena occurring in the majority of chemical engineering processes. They also serve as a basis for exposing the students to modeling of real phenomena. This was a very exciting part of this new course, which is an important basis for the new curriculum we have developed at the University of Cape Town. It has also given students something to refer back to when they encounter the theory that uses these phenomena later in their studies.

Full details of the experiments may be obtained by e-mailing the author at dmf@chemeng.uct.ac.za

ACKNOWLEDGMENTS

I wish to acknowledge the help received from God, the Creator of the universe, both in giving me the creativity needed to generate these ideas and for placing the correct material in my path at just the right time. I also wish to thank my two younger children, Andrew and Ann (ages 14 and 12 at the time) and our friend Brett Melville (age 17 at the time), for helping me perform the experiments to get the data for modeling and for their keen observations, patience, and ideas for extra measurements to take.

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Random Thoughts . . .

SPEAKING OF EDUCATION II[1]

RICHARD M. FELDER
North Carolina State University • Raleigh, NC 27695

◑ *If a doctor, lawyer, or dentist had 40 people in his office at one time, all of whom had different needs, and some of whom didn't want to be there and were causing trouble, and the doctor, lawyer, or dentist, without assistance, had to treat them all with professional excellence for nine months, then he might have some conception of the classroom teacher's job.*

Donald D. Quinn

◑ *Thoroughly to teach another is the best way to learn for yourself.*

Tryon Edwards

◑ *You do not really understand something unless you can explain it to your grandmother.*

Albert Einstein

◑ *It is noble to be good, and it is nobler to teach others to be good—and less trouble!*

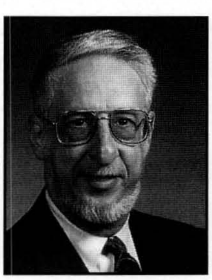
Mark Twain

◑ *The task of the excellent teacher is to stimulate "apparently ordinary" people to unusual effort. The tough problem is not in identifying winners: it is in making winners out of ordinary people.*

K. Patricia Cross

◑ *I am not impressed by the Ivy League establishments. Of course they graduate the best: it's all they take, leaving to others the problem of educating the country. They will give you an education the way the banks will give you money, provided you can prove to their satisfaction that you don't need it.*

Peter De Vries



***Richard M. Felder** is Hoechst Celanese Professor of Chemical Engineering at North Carolina State University. He received his BChE from City College of CUNY and his PhD from Princeton. He has presented courses on chemical engineering principles, reactor design, process optimization, and effective teaching to various American and foreign industries and institutions. He is coauthor of the text* Elementary Principles of Chemical Processes *(Wiley, 1986).*

◑ *One mark of a great educator is the ability to lead students out to new places where even the educator has never been.*

Thomas Groome

◑ *When you teach well, it always seems as if 75% of the students are above the median.*

Jerome Bruner

◑ *If at first you do succeed, try to hide your astonishment.*

Source unknown

◑ *Picture yourself in France in a cave with prehistoric drawings on the wall. These drawings tell a story and were perhaps the first use of technology for educational purposes. Now, thousands of years later, professors are still drawing on walls!*

Bruce Finlayson

◑ *The best learners...often make the worst teachers. They are, in a very real sense, perceptually challenged. They cannot imagine what it must be like to struggle to learn something that comes so naturally to them.*

Stephen Brookfield

◑ *The vanity of teaching often tempteth a man to forget he is a blockhead.*

George Savile

◑ *Football combines the two worst elements of American society: violence and committee meetings.*

Herb Childress

◑ *University politics are vicious precisely because the stakes are so small.*

Henry Kissinger

◑ *The teachers who get "burned out" are not the ones who are constantly learning, which can be exhilarating, but those who feel they must stay in control and ahead of the students at all times.*

Frank Smith

◑ *When Pablo Casals reached ninety-five, a young reporter asked him a question: "Mr. Casals, you are ninety-five and the greatest cellist who ever lived. Why do you still practice six hours a day?" Casals answered, "Because I think I'm making progress."*

◑ *Don't say you don't have enough time. You have exactly the same number of hours per day that were given to Helen Keller, Louis Pasteur, Michelangelo, Mother Teresa, Leonardo da Vinci, Thomas Jefferson, and Albert Einstein.*

H. Jackson Brown, Jr.

◑ *Ninety-five percent of this game is half mental.*

Yogi Berra

◑ *I can't give you a brain, but I can give you a degree.*

The Wizard of Oz

[1] See also "Speaking of Education," *Chem. Engr. Ed.*, **27**(2), 128 (1993)

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/

INTEGRATING PROCESS SAFETY INTO ChE EDUCATION AND RESEARCH

M.S. MANNAN,* A. AKGERMAN, R.G. ANTHONY, R. DARBY, P.T. EUBANK, K.R. HALL
Texas A&M University • College Station, TX 77843-3122

Accident statistics for 1989 from the Accidental Release Information Program (ARIP) of the U.S. Environmental Protection Agency[1] are shown in Figure 1. These statistics cover catastrophic and unplanned releases of chemicals into the atmosphere. They underline the fact, however, that a large number of accidents and catastrophic releases occur because of design flaws, wrong equipment specifications, and lack of or disregard for operating and maintenance procedures. The boardroom perspective on the cause of these accidents and what to do about them varies, but many believe that safety in the process industry is of primary importance and is critical to the industry's continuing "license to operate."

The total number of process plant accidents cannot be accurately estimated because of underreporting, but the number is large and many people, both workers and the public, are adversely affected by the accidents. For example, in 1991 the National Response Center received over 16,300 calls reporting the release or potential release of hazardous chemicals.[2] Another study[3] analyzed the EPA's Emergency Response Notification System database of chemical accident notifications and found that from 1988 through 1992, an average of nineteen accidents occurred each day, *i.e.*, more than 34,500 accidents involving toxic chemicals occurred over the five-year period. The promulgation of the Toxic Release Inventory Reporting requirements[4] as part of the Clean Air Act Amendments of 1990 led to the submission of toxic release information that clearly delineated the number and extent of toxic chemical releases and their potential impact on the public and on the environment. The university plays a critical role in changing this situation.

Change in population demographics, increasing awareness of process plant hazards, and above all, the continuing threat of a chemical catastrophe continue to provide the impetus for governments to develop legislation for eliminating or minimizing the potential of such accidents. International efforts include the Seveso Directive covering members of the European Community. Other nations have similar laws, such as the Sedesol guidelines in Mexico for performing process risk audits, and the post-Bhopal accident-prevention law in India. The World Bank has developed guidelines for identifying and controlling hazards, and the International Labor Organization has developed a code of practice for preventing major accidents.

In 1990, the U.S. Congress enacted the Clean Air Act Amendments (CAAA), which directed the Occupational

M. Sam Mannan *is Associate Professor of Chemical Engineering at Texas A&M University and Director of the Mary Kay O'Connor Process Safety Center. He received his BS degree from the Engineering University in Dhaka, Bangladesh, and his MS and PhD degrees from the University of Oklahoma. His research interests include process safety and risk management, quantitative risk assessment, reactive chemistry, and fate and transport modeling of chemical releases.*

Aydin Akgerman *is the Chevron II Professor of Engineering in the Chemical Engineering Department at Texas A&M University. During his career he has taught at Bogazici University and Ege University (in Istanbul and Izmir, Turkey, respectively), and at Texas A&M University. He has also worked as the R&D Manager at Cimentas Izmir Cement Plant.*

Rayford (Ray) G. Anthony *is the C.D. Holland Professor of Chemical Engineering and Head of Chemical Engineering at Texas A&M University. He received his BS degree from Texas A&M University and his PhD from the University of Texas. His research interests include development of catalysts and modeling catalytic reactors, and mathematical modeling of multiphase reactors.*

Ron Darby *is Professor of Chemical Engineering at Texas A&M University. He holds a PhD degree from Rice University and has been at Texas A&M since 1965. His primary research interests are flow of complex fluids, two-phase flows, viscoelastic and non-Newtonian fluids, slurries and suspensions, and process safety.*

Philip T. (Toby) Eubank *is Professor of Chemical Engineering at Texas A&M University. He received his BS degree from Rose-Hulman Institute of Technology and his PhD from Northwestern University. His research interests are in the thermo-physical properties of fluids and fluid mixtures plus electrical discharge machining.*

Kenneth R. Hall *is the GPSA Professor of Chemical Engineering and Director of the Thermodynamics Research Center at Texas A&M University. During his career, he has worked with AMOCO and ChemShare and has taught at the University of Virginia and Texas A&M University.*

* *Corresponding author.*

Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA) to develop standards for reducing the frequency and severity of chemical plant accidents. In keeping with the congressional mandate, OSHA promulgated the Process Safety Management (PSM) rule, intended to protect workplace employees. Similarly, EPA promulgated its risk-management program rule in 1996 to protect the public and the environment. In the United States, federal agencies are not the only government regulators active in the chemical accident prevention arena. Several states have empowered their health, safety, and environmental agencies to create regulations requiring companies to establish and practice specific programs to improve safety.

Laws and regulations are logical reactions to catastrophic process plant accidents. But can the mere promulgation and enforcement of laws and regulations actually affect the frequency and severity of process plant accidents? The philosophical issue is that we can only regulate something for which we have knowledge and understanding. For example, OSHA process safety management regulations require facilities to develop and implement management of change procedures. That is, before a process change is implemented, engineers must evaluate the change and ensure that it is technically sound and cannot result in a hazardous situation. The evaluation could consist of a hazard and operability (HAZOP) study conducted by a multidisciplinary team using some HAZOP software available in the marketplace.

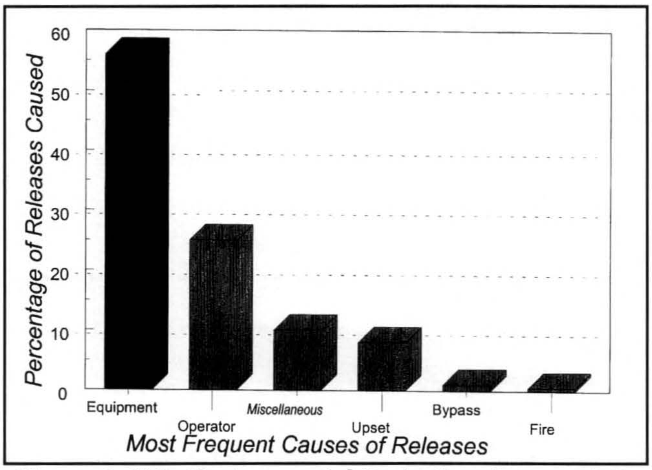


Figure 1. U.S. Environmental Protection Agency statistics on Accidental Release Information Program, 1989.

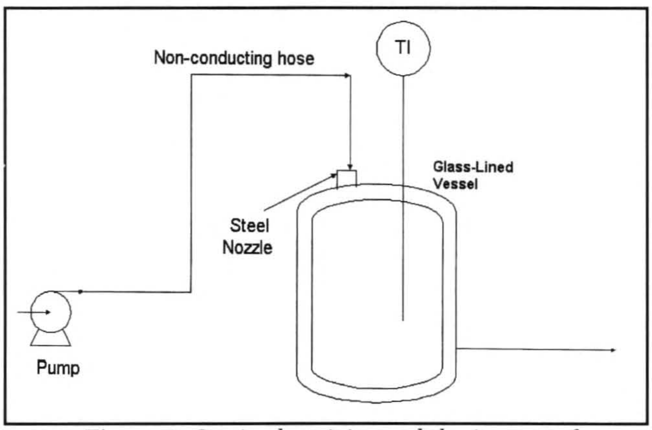


Figure 2. Static electricity and the impact of process changes.

For the process shown in Figure 2, consider the addition of an organic A with a certain thermal conductivity to the glass-lined reactor. During the original design, engineers made necessary calculations to ensure that the voltage and ignition energy caused by static electricity did not exceed the dangerous limits of 350 V and 0.1 mJ, respectively. Above these limits there exists a potential for spark and possible fire and explosion. But in response to market demands for product specifications, the plant is planning a switch to organic B, the only difference in thermophysical properties being a slight increase in thermal conductivity. The calculations now show that the voltage and ignition energy caused by the static electricity exceeds the dangerous limits. The most important question is whether we make this determination as part of an after-the-fact accident investigation or as part of the management of change process. If we choose the latter, we must understand the gravity of the problem and take appropriate corrective and remedial measures. These measures may include installation of additional grounding, control of flow rate to reduce static electricity, and relaxation (hold time to allow for charge reduction).

In addition to the above issues, the issues of inherent safety in process design, equipment selection, and operating and maintenance procedures depend to a large extent on a fundamental understanding of the underlying science and application of those principles to the problem at hand. For example, in design and construction of a polyethylene plant that uses a large amount of flammables at very high pressures and temperatures, the inherent hazard is that any accident has the potential of releasing large quantities of the flammable, which because of the thermodynamics can likely flash and form an aerosol. While "bells and whistles" can be added after the fact to make the process extrinsically safer, the comprehensive education and research approach suggested in this paper equips the engineer to come up with an intrinsically safer process during the design and construction phase. Some solutions may include intensification, substitution, attenuation, or limitation of effects. These concepts, while available in some literature,[5-7] are not covered adequately in chemical engineering instruction and research.

What can we do to fix or reduce the extent of the fundamental problem described here? The challenge is how to create a culture in which consideration of process safety issues is second nature, driven by a total understanding of the underlying engineering, process chemistry, and other factors. While regulations, plant policies and procedures, and industry standards accomplish much, universities must play a significant role in addressing this challenge. The role of engineers has changed dramatically, and as a result, universities must provide an integrated engineering education that equips engineers not only with the classical fundamental subjects (thermodynamics, fluid mechanics, reaction kinetics), but also provides them with an understanding of process safety engineering and how they can use their knowledge of fundamental engineering subjects to make the process plant safer. The need is not the establishment of a new discipline, but one of fine tuning the engineering curriculum. To this end, Texas A&M University established the Mary Kay O'Connor Process Safety Center, an industrially sponsored Center of Excellence, to produce engineers trained in process safety and to provide industry with the research base it needs to compete successfully in the global marketplace.

> ***The challenge is how to create a culture in which consideration of process safety issues is second nature, driven by a total understanding of the underlying engineering, process chemistry, and other factors.***

The Center charter is to broaden the scientific and engineering knowledge base of industry and to educate engineers and scientists in the field while striving to achieve technological breakthroughs necessary to reach ambitious long-term, systems-level engineering goals. Its mission includes bringing together researchers from diverse industrial, academic, and governmental laboratories whose work can contribute to the development of process safety issues that can have a far-reaching impact on the chemical processing industry. The Center also has the responsibility of outreach to industry, to other universities and educational institutions, and to the public as a whole. A program at the Michigan Technological University bears certain similarities insofar as the educational and research component is concerned. As illustrated by the following discussion, however, the Center programs span not only education and research, but also include training, service, information dissemination, and symposia.

The Center has also recently established a dialogue with the Center for Chemical Process Safety (CCPS) in order to coordinate activities for accomplishing mutually desirable process safety goals. While CCPS also focuses on making an impact on process-safety-related issues, the Center's goals and objectives are much deeper. They include shifting the paradigm to safety being second nature and incorporating process safety into the curriculum. The Center programs and activities are meant to complement and enhance the CCPS efforts. Success toward these goals at Texas A&M University is a first step in this process. Future plans include activities to encourage similar initiatives at other institutions. Based on the availability of funds, these activities could include joint projects or grants to encourage teaching and research in the areas of process safety. The Center is working on several proposals that could lead to joint projects with other universities under grants provided by government agencies.

GOALS OF AN INTEGRATED APPROACH

The first step in accomplishing the goals and objectives from the university perspective is for educators to recognize that process safety should be integrated into a comprehensive instructional and research program. For example, is it appropriate for educators to teach process design courses without adequately covering concepts of inherently safe design and other process safety concepts? Is a course on reaction engineering complete without due treatment of runaway reactions, the causes of such reactions, and what role an engineer might have in preventing them? Finally, offering the opportunity for students to take specific process safety engineering courses is critical in the integrated approach. Research should be directed toward developing safer processes, equipment, procedures, and management strategies that will minimize losses within the processing industry. The goals of an integrated approach span a large spectrum of issues focused toward programs and activities that encourage safety as second nature. The goals cover four broad areas: instruction; information storage, retrieval, and analysis; service; and research. Some of the general goals include

- *Marshaling all the resources of the university that can be applied to process safety and risk management, advertising these capabilities, and bringing these resources together to solve complex problems that require multidisciplinary teams*
- *Developing the capability to respond quickly and effectively to the research needs of other organizations*
- *Attracting outstanding faculty, researchers, practitioners, and students to participate in process safety research programs and activities*
- *Sponsoring or participating in safety-related events such as symposia and design contests*
- *Serving as a role model in good safety practices for other institutions and within the University*

Of these general goals, attracting outstanding faculty, researchers, practitioners, and students is by far the most critical. The extent of the problem is illustrated by the fact that because of industry initiatives and regulatory requirements, process safety engineering and associated technologies have become an essential feature of all chemical processing design and operations. But almost all universities lack effective teaching and research programs to support the needs of industry. This situation can be changed only by putting in motion a cycle that irrevocably changes the paradigm. For example, we could produce several chemical engineering PhDs per year with specialization in process-safety engineering, and they could then go on to teach at other universities or conduct beneficial research in solving process safety problems. Thus, the courses they teach (including classical engineering courses) would contain a comprehensive approach including consideration of all process safety issues. In addition, their research would definitely include the solution of many process safety problems.

EDUCATION

The educational programs of the Center are based on a three-pronged approach. First, to establish a series of undergraduate and graduate courses dedicated specifically to process safety engineering. Second, to act as a catalyst for incorporating process safety problems into existing courses such as design, reaction kinetics, and thermodynamics. Third, to sponsor training of engineering faculty through participation in continuing-education short courses covering process safety. The overall goals in education include

- *Improving knowledge and awareness of process hazards and safety for faculty, students, engineers and other professionals, plant workers, public safety personnel, transportation workers, and the public*
- *Developing state-of-the-art educational tools, undergraduate and graduate courses, and continuing-education programs*
- *Producing engineers with a good education in safety*

The current program of the Center includes an interdisciplinary, elective course in process safety engineering that is cross-listed between chemical engineering and safety engineering programs and has been taught for the last three years. The course is one of the most popular electives in the department. A graduate counterpart of the course has also been developed and taught.

The Center promotes the use of SACHE modules within traditional chemical engineering courses. In addition, to increase faculty awareness, the Center sponsors participation in continuing education short courses on process safety. The intent is to provide information on state-of-the-art safety technologies as well as to encourage faculty to use these courses as opportunities to update process safety elements in the traditional chemical engineering courses. To date, various faculty have attended the following courses:

- *Engineering Design for Process Safety*
- *Tools for Making Acute Risk Decisions*
- *Methods for Sizing Pressure-Relief Valves*
- *Fundamentals for Fire- and Explosion-Hazards Evaluation*
- *Use of HAZOP Studies in Process-Risk Management*
- *Human-Error Evaluation and Human-Reliability Analysis for Chemical Process Systems*
- *Safe Automation of Chemical Processes*
- *Consequences of Vapor Cloud Explosions, Flash Fires, and BLEVEs*
- *Vapor Cloud Dispersion Modeling*

The Center has begun an aggressive program to provide continuing-education courses to practitioners in industry. The intent is to provide training at outreach locations in a format that allows attendees to take the short courses without having to travel long distances and with minimal disruptions in their work schedule. We started with a 13-course syllabus at two campuses: Texas A&M University System Galveston campus and the Texas Engineering Extension Service Pasadena training facility. The courses, taught by both industry and university experts, meet Monday and Tuesday from 8am to 5pm. Continuing education credits are provided for all short courses and attendees may choose to take structured series of courses and receive certificates of attendance for a specific program.

The Center has future plans calling for continued growth and expansion of the efforts already underway. Several advanced-level courses on process safety and associated technologies are being developed. They can be taught by a multidisciplinary team of instructors and offered at multiple campuses through distance-learning technology. Some of the courses under consideration for development include

- *Mechanical integrity of process plants (potential teaming between chemical and mechanical engineering departments)*
- *Advanced topics in safety and environmental management (potential teaming between chemical engineering, industrial engineering, and chemistry departments)*
- *Quantitative risk assessments (potential teaming between chemical engineering, statistics, and business administration departments)*

In the continuing education program, the Center plans to add appropriate courses as necessary, but the ultimate objective is to move from the current campus-oriented offerings to an interactive distance-learning system. Texas A&M University has already implemented distance-learning curricula in the industrial engineering department. The Center intends to collaborate with industrial engineering to develop distance-learning course modules for both graduate courses and continuing education courses.

Within the next few years, MS and PhD graduates in chemical engineering will be finishing their degree programs with emphases in process safety engineering. The degree programs for these graduates will include

- *Traditional core chemical engineering courses*
- *Additional process-safety-specific courses*
- *MS or PhD theses addressing the solution of an engineering problem related to process safety*

INFORMATION STORAGE, RETRIEVAL, AND ANALYSIS

One of the main causes of process safety incidents in the chemical processing industry is the lack of access to necessary information and data. The problem is threefold: first, in many cases the information does not exist; second, even when some information and data are available, accuracy and credibility are questionable; and third, when information exists, it is not well organized or easily accessible. Thus, in the area of information storage, retrieval, and analysis, the Center's goals include

- *Gathering and storing information related to chemical process safety, including case histories, equipment and human reliability*
- *Developing computer databases and user interfaces to provide easy access to and analysis of this information*
- *Analyzing the information and publicizing the results*

The heart of the Center work is its library, which includes books, articles, reports, journals, and other documents focusing on engineering aspects of process safety (*e.g.*, relief systems, dispersion modeling, safe design) as well as the social, economic, and behavioral aspects of process safety incidents and natural disasters. Various software programs are also available. The holdings are cataloged in a computerized bibliographic database. The library catalog is available on-line on the Center website, enabling web browsers to search the library materials for specific publications.

The Center publishes the *Centerline* three times a year. It contains technical and research issues of interest in the field of process safety and risk management. It is also available on the Web site (http://process-safety.tamu.edu/). The site provides information on process safety-issues, publications, and other items of interest for process-safety and risk-management topics. It also allows individuals, companies, and organizations to browse actively and to acquire information on process-safety-related subjects. Access is free and allows the user to conduct interactive searches and provides computations, analyses, and calculations. The site contains information on research, technical papers and reports, access to the library database, regulations, frequently asked questions, access to software, links to other appropriate sites, electronic *Centerline* issues, and announcements for symposia, seminars, and short courses. The site is updated regularly to provide new items and state-of-the-art techniques to users.

Future plans for information storage, retrieval, and analysis include development of computer databases and user interfaces to provide easy access and analysis of process-safety-related information. For example, one item under consideration is development of an incident-history database with fuzzy search capability. This effort can expand to develop an interactive teaching module providing Web-based training. Also, efforts are underway to establish a Process Safety Newsgroup (PSN) that would provide an open forum for exchange of ideas and questions for personnel involved in the process-safety and risk-assessment fields. The purpose of PSN would be to facilitate the exchange of ideas and information among U.S. and international public- and private-sector organizations about prevention of, preparations for, recovery from, and/or mitigation of risk associated with catastrophic accidents in chemical processing facilities.

Another current project is analysis of accident databases to pinpoint specific causes and to determine areas of needed research. The intent is to use the results to determine areas of critical need and to focus efforts on those areas. At this time, the project consists of analyzing portions of the EPA Accidental Release Information Program to develop a strategy of how these databases can be used to improve process safety.

As new information is compiled and research results become available, the Center will disseminate them as widely as possible. In many cases, it may be necessary to publish monographs, research papers, and guidelines. The changing environment and needs of industry dictate, however, that we consider advanced electronic media such as CD-based publications and internet communication.

SERVICE

The mission of a university and its faculty includes providing service to industry and society. The changing nature of the chemical engineering profession necessitates that we take a closer look at how we provide this service. Universities and faculty are remiss if they do not play an adequate role in ensuring public safety. Another issue is that a large number of process plants exist that are either owned by small companies or are so-called "mom-and-pop" operations. An accident from such a small facility has the potential of severe consequences and can damage the whole industry's "license to operate" just as does an accident in a large plant. The larger facility probably has resources, training, and equipment to either prevent the accident in the first place or to respond to the consequences if it does occur, however, while the small facility probably lacks proper awareness, training, and information. Thus, the Center's goals include

- *Providing service to small and medium enterprises, government agencies, institutions, local emergency planning committees, and others to evaluate and minimize risks*
- *Providing independent accident investigation and analysis services to industry and government agencies, particularly for those accidents that suggest new phenomena or complex technologies*

In the area of service to small business, the Center seeks collaborative efforts with government agencies (both state and federal), professional and trade organizations, and industry. Another area of interest for the Center is accident investigation. The Center objective in looking at accidents is fourfold; first, identifying multiple accidents that may exhibit common phenomena; second, finding accidents that suggest new phenomena related to basic research or fundamental issues; third, providing independent third-party evaluation, peer review, or critique of accident investigations conducted by government agencies; and fourth, researching accident investigation techniques and issuing research reports with recommendations for the best possible accident-investigation techniques. Development of software and tools for accident investigation is also an area of interest.

RESEARCH

The overall goals of the research program aim at improving safety in process plants by identifying the greatest risks and then developing inherently safer processes and designs, developing best-practice databases, and solving problems identified by industry. The research goals of the Center include

- *Systematically identifying the greatest risk in terms of severity of consequences and probability of occurrence and prioritizing them*
- *Systematically identifying projects that could be undertaken by the Center and would most effectively address the risks identified by risk analysis*
- *Developing safer process schemes for the most common and most hazardous processes; developing design concepts for implementing such processes*
- *Developing devices, systems, and other means for improving safety of chemical operations, storage, transportation, and use by prevention or mitigation*
- *Improving means for predicting and analyzing the behavior of hazardous chemicals and the systems associated with them*

Current research activities include a reactive systems research and teaching laboratory established for evaluating the reactivity of chemicals and mixtures of chemicals, and to obtain data needed to size relief systems for runaway reactions. A reactive systems screening tool (RSST) exists and operating procedures have been prepared based on two base-case runaway reactions: methanol and acetic anhydride (tempered) and hydrogen peroxide (gassy). The RSST studies can be used for initial reactivity characterization and vent sizing, as well as for a laboratory experiment in the undergraduate unit operations laboratory.

Another research project underway is "Two-Phase Viscous Flow Through Safety Relief Valves." Phase I of the project includes a survey of the literature and evaluation of state-of-the-art procedures for relief-valve sizing in two-phase flow, verification of various theoretical models by experimental data, and recommendation of design practices for viscous two-phase flow through safety-relief valves. Phase II involves experimental design for Phase III, which is the experimental phase. The program includes CFD numerical computation and prediction of two-phase flow through safety relief-valves.

Other research includes "Post-Release Transport and Fate of Toxic Chemicals and Their Mixtures." The objective is to develop mathematical models that accurately represent the transport and fate of chemicals as well as their mixtures resulting from process-plant accidents. Some computer models are available that can be used to make these calculations, but many problems are associated with their application, including problems in handling polar substances and mixtures. Our objective in conducting this research is to address this problem and to develop an approach that can be applied consistently and uniformly.

Future plans for research include establishment of a state-of-the-art reactive chemicals laboratory. The Center has acquired and installed an Automatic Pressure Tracking Adiabatic Calorimeter (APTAC) for reactive screening of chemical reaction compounds and mixtures. The APTAC can be used for thermal analysis of solid or liquid chemicals or for gas/liquid, liquid/liquid, gas/solid, and liquid/solid mixtures. It can obtain time-dependent kinetic data and temperature and pressure profiles for both open and closed systems. It can also be used for process simulation of batch and semi-batch reactions, fire exposures, emergency relief venting, and physical-properties measurement. The resulting information can identify potential hazards and tackle key elements of process safety design such as emergency relief systems, effluent handling, process optimization, and thermal stability.

The Center Steering Committee from time to time evaluates proposals and ideas regarding future research projects. Depending on the situation, funding for these projects is sought from external sources or from internal Center funds. For example, some of the projects currently under consideration are

- *Corrosion-induced fatigue failure for moving parts (correlation between corrosion rates, failure frequency, and intensity of movement)*
- *Methodologies on inherent process safety*
- *Comprehensive database for equipment and component failure rates in the chemical industry*
- *Incident history database*
- *Data integrity and compilation during engineering projects*
- *Human factors research*
- *Thermodynamic data for specific mixtures (e.g., 30% oleum)*
- *Flammability limits and explosivity limits (both experimental and correlation)*
- *Use of computational fluid dynamics to evaluate damage to facilities based on knowledge of gas concentrations in cloud, confinement, and dynamic response of structures*
- *Passive explosive suppression in compartments for offshore structures*
- *Safety protective data and linkage with fire-school activities*
- *Fire suppression with environmentally friendly chlorofluorocarbons*

Continued on page 209

Experiments With INTEGRATION OF EARLY ENGINEERING EDUCATION

VINCENT G. GOMES, TIMOTHY A.G. LANGRISH
The University of Sydney • Sydney, New South Wales 2006, Australia

Engineering education traditionally places initial emphasis on "exposition," followed by "application," within the domain of a specific course. Subject matter is programmed so that the general and inclusive ideas of the discipline are presented first, followed by progressive differentiation in terms of detail and specificity. Often, in the early years of engineering education, exposition and applications phases dominate the curriculum, while integration receives scant attention. With the current urgency to provide a well-rounded learning experience, skills in addition to conventional engineering abilities are being stressed at all levels in academia, including the early formative years when the science content dominates the curriculum.

A typical engineering teaching plan includes

- *Exposition of scientific principles*
- *Exposition of engineering principles*
- *Acquisition of practical and theoretical skills*
- *Application of acquired skills and knowledge to solve complex problems*

Appropriate assessment and feedback then follow. A systems analogy version of traditional education in terms of the stimulus, response, and feedback process is that the input of teaching material, the input from students, the course goals, and the outcomes all feed into the course itself (see Figure 1).

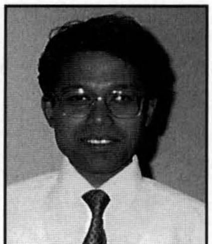
An important detail missing from this unidimensional approach relates to the multidimensional, distributed, and interactive nature of learning (drawing from the systems analogy) and consequently the complex multivariable structure of the educational process. Further, most of the relevant application phase usually occurs toward the end of the degree curriculum (in the form of design and thesis), often long after the principles have been taught. If we recognize that all aspects of learning should be interrelated, then educators need to explore appropriate integrative learning tools to avoid excessive fragmentation of curriculum and to foster interaction among the participants.[1-3]

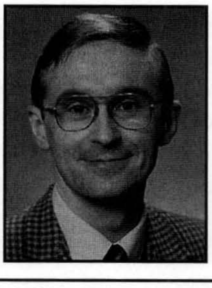
This article highlights the dangers of excessive fragmentation in course presentation, especially in the early stages of engineering education. A lack of relationship between courses could also create rigid compartmentalization of knowledge. Our attempts to encourage cooperative learning and integrative reconciliation (systems analogy) between courses will be discussed.

A PROBLEM AREA AND POSSIBLE SOLUTION

Early engineering courses rich in scientific content attempt to introduce key principles and tools so that more detailed and differentiated material may follow and provide the scaffolding for further learning. But it is common to find that little effort has been spent in creating links between the courses. For effective problem solving, it is necessary to have an integrated cognitive structure for flexible retrieval

Vincent Gomes *received his MEng and PhD degrees from McGill University and his BTech degree in chemical engineering from IIT. He is currently a Senior Lecturer in the Department of Chemical Engineering and Program Manager of the Australian Key Center for Polymer Colloids at the University of Sydney. His research interests include polymer engineering, sorption-reaction, and pollution prevention.*





Tim Langrish *received his BE degree in chemical and process engineering in New Zealand and his DPhil at the University of Oxford. After working as a Research Fellow with the Separation Processes Service at Harwell Laboratory, he returned to the University of Canterbury in New Zealand and subsequently took a position at the University of Sydney. His research interests include drying technology and fluid mechanics.*

and application of acquired tools. Thus, the convenient practice of minutely segregating a discipline into courses and sub-courses is often insufficient for deep learning. Courses offered in parallel or in sequence, served in bite-size chunks for ease of digestion, often appear confined within watertight compartments that serve their specific purpose, with little time left for forays into neighboring territories. Such methods may be responsible for eliciting student responses such as "...that was taught in fluid mechanics...are we supposed to know it for heat transfer?"

Studies[4,5] show that the early formative years in engineering education are crucial in engendering a professional attitude and weaning students away from their high school attitudes. The first- and second-year students face a range of diverse subjects, involving various faculties, with seemingly minimal connections between them. Students fail to see any relationship between the early courses and their chosen professional discipline. Ideas, concepts, and applications are commonly presented in the context of a particular course without recognition of courses taught in parallel. This practice frequently results in substantial segregation between courses without relational mapping and may foster a disposition toward rote memorizing, which in turn results in loss of associative learning in the initial stages.

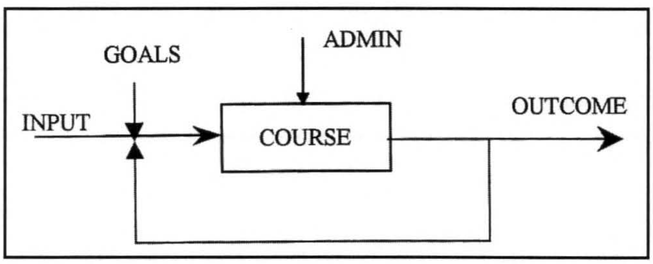


Figure 1. *Systems analogy of unidimensional curriculum experience.*

A message that needs to be emphasized early on is that as a body of knowledge, chemical engineering has structure and form, is built on fundamental laws, concepts, empirical observations, and data that we believe are self-consistent. Our discipline is not an unrelated collection of a few thousand equations put together to solve problems in a "cookbook" manner. Students must be guided to avoid missing the forest for the trees. They often do not see any relationship between concurrent courses, but view them as isolated hurdles to be overcome sequentially, and they perceive that lessons learned in a particular subject will not come under rigorous tests within the framework of a different course. This implies that the provision of a "road map" of the discipline, showing links between the different courses and how they fit in, may be advisable. This aspect is currently being explored in our department.

For efficient delivery of a large body of knowledge, minimal overlap tends to exist between syllabi of different courses. As a result, students continue to solve unidimensional, specialized problems tailored for a specific course. The postponement in training to solve multifaceted problems continues for the major part of undergraduate education. Thus, crucial connective links between different courses may remain hidden for the majority of students. The consequence is a distorted view of real-life problems that have been massaged in view of a specific course syllabus.

Meaningful learning is by definition relatable and anchorable to established ideas in the cognitive structure.[6] Thus, it is not uncommon to find that the structure of the discipline is unclear in the early stages of engineering education, sometimes resulting in lack of motivation and interest. It is often only in the final stages of a degree program that advanced students have opportunities for integrating their learning through thesis and design work involving challenging problems.

Rigid compartmentalizing implies that equations and methods memorized to solve typical problems for respective courses would not be flexibly available for solving "open-ended, real-life" problems. A review or refresher material within a course may temporarily help retrieve "lost information." Thus, integration is important not only within the confines of a course (intra-course), but also in relation to the discipline and courses conducted in parallel. Therefore, following a detailed exposition and application phase within separate courses, a mechanism for integration of the subject matter is desirable.

FIELD TRIAL

In order to encourage course integration, three years ago we started the practice of collaborating with other instructors within the department to devise a single joint project that would count for both courses. The final project is normally carried out in small groups, often with minor technical variations for each group, thus encouraging cross-fertilization within and between the groups without duplication. The presentation of results in formal reports, and often orally, provide further opportunity to improve verbal and writing skills.

At the University of Sydney, we offer Material and Energy Balances and Process Case Studies during the first year. During the second year, Chemical Engineering Computation is offered as a sophomore problem-solving course, involving nonlinear equations, interpolation, least-squares, and numerical calculus, while the parallel Fluid Mechanics and Heat and Mass Transfer courses focus on the fundamental principles of corresponding transport processes and on equipment design. The remaining courses during the first and second years involve other faculties. We decided to set joint end-of-course projects that would highlight the lessons learned in each of the engineering courses during the first and second years, and also to combine elements from each course to solve a complex engineering problem.

Our course schedule permitted setting a joint project on early process design (Flowsheet of a Bio-Refinery) for Material and Energy Balances and Process Case Studies during the first year, and on fluid flow analysis/optimization for Fluid Mechanics and Chemical Engineering Computation during the second year. Our objectives were

- *To attempt integration between two courses*
- *To solve a nontrivial problem*
- *To provide early analysis and synthesis experience*
- *To encourage team effort*

Typically, the classes were divided into four- or five-member groups composed of weak, average, and strong students (based on their grade-point average). The groups were drawn from concurrently offered courses; thus, there were often a few students (6-8) who were not part of one or the other course. These students were distributed into groups so that there were at least two members taking both courses. The management and task allocation were left for the group members to arrange. Initial instructions to help the teams function effectively were provided through preparation sessions in which professional roles and responsibilities were discussed and group responsibilities were produced in written form.

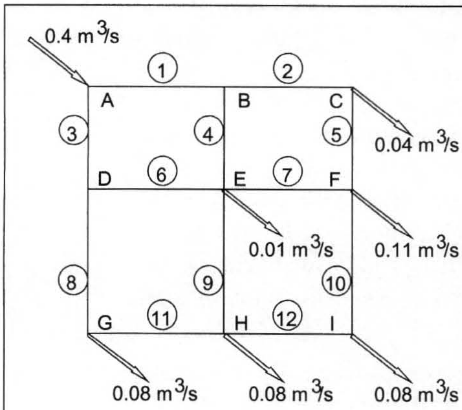
Opportunities were provided for the group members to meet during the tutorial hours and on their own. Every group member was asked to assess their peers' efforts (on a scale of 0-10) and to indicate the actual contribution of each group member in a section on "who did what" attached to the final

TABLE 1: PIPE NETWORK ANALYSIS

PROBLEM STATEMENT

In order to specify appropriately sized flowmeters for monitoring the water flowrates in the cleaning-water distribution network at the Waikikamukau Dairy Cooperative, you are required to estimate the flowrate in each pipe in the system, shown diagrammatically in the figure. You must use a systematic technique for this problem.

- The total flowrate of 0.4 ms^{-1} enters the system at point A. Cleaning equipment draws off the indicated flows at points C, E, F, G, H, and I.
- Ignore the effects of differences in elevation. Water may be assumed to have a kinematic viscosity of $10^{-6} m^2 s^{-1}$, and all the pipes are made of carbon steel.
- You must use both a spreadsheet and a FORTRAN program to carry out the iterative calculations, but you must first do a hand calculation for one iteration of your method. You must then include a printout of your spreadsheet for this case and the results of the FORTRAN program to validate your computer code. Record the time that you spend on each approach (spreadsheet and program) and comment on the ease of use of each approach for this application.
- You must document the spreadsheet fully and clearly, and also include an attachment specifying the formulae used in the cells together with the order of calculation.
- For the FORTRAN program, each step in the program must be clearly documented, and you must attach an explanation of the order of calculations (a flow chart may be a useful way of doing this). The formulae used at each step of the calculation must also be specified.
- Relationships between the friction factor, the Reynolds number, and the relative roughness are given in Perry's *Chemical Engineers/ Handbook* and in Coulson and Richardson, Volume 1. It is your responsibility to use formulae appropriate for the range of Reynolds numbers and data given.
- While your submissions should be tidy, handwritten attempts will not be penalized compared with typewritten ones, provided that the material can be readily assessed.
- You must present a summary page at the front of the submission, giving your group number and a table showing the following results for each pipe:



Pipe Data

Pipe No.	Length (m)	Diameter (m)
1	100	0.3
2	100	0.3
3	125	0.4
4	125	0.2
5	125	0.3
6	100	0.3
7	100	0.2
8	250	0.25
9	250	0.3
10	250	0.2
11	100	0.3
12	100	0.2

1. Direction of flow
2. Average velocity
3. Volumetric flowrate
4. Pressure drop

- You must explain all your calculations, document your FORTRAN program and your spreadsheet, and hand in printouts of your spreadsheet, your program, and the results from the program.

Analyses and Discussion Topics

1. Why is more than one iteration necessary in order to get a converged solution, even with a problem involving only two pipes?
2. Why do problems with many pipes (and "loops" of pipes) take more iterations to converge than a two-pipe problem?
3. What would happen if all the pipe diameters were doubled? Would the flowrates be the same in all the pipes? If not, why not?
4. Is your final solution sensitive to the initial guess?
5. If all the flowrates into and out of the system were increased by 10%, would all the flowrates within the system also increase by 10%?
6. How much different would the flowrates be (for the original inlet and outlet flowrates) if the pipes were completely smooth?
7. Suggest globe valves for flow regulation and check valves for back-flow prevention at appropriate points. If a centrifugal pump is installed for supplying water from a tank and the outgoing flows are connected to specified equipment, show how these affect your calculations.

submission. The lecturers and tutors monitored the individual group members during the tutorial, and class hours were assigned for the project. At the conclusion of the project, team members were questioned on the technical aspects of the project such that team members were individually held responsible for the entirety of the project content. This input formed the basis for awarding a final mark to an individual student. The final mark was the team project grade modified by up to twenty percent according to the results of the peer-effort assessments and the interviews such that the average mark for the individuals in the group was the same as the team mark. Evidence whether the group process was working was noted during the tutorials themselves.

Apart from the initial instructions on how to function as a team, support was offered to help teams function effectively if it was needed. Otherwise the groups were encouraged to gain autonomy and to promote internal communication with a minimum of staff intervention. The students approached the problem through internal coordination, sharing of common difficulties and insights, encouraging weaker students, fostering a sense of responsibility, accountability, and creation of memorable situations. The average duration of the shared project was about four weeks before the termination of the semester and the projects were typically assessed at fifteen percent of the total course marks for each of the courses.

An example of one of our problem statements is summarized in Table 1. The problem on pipe network analysis using fluid mechanics principles, was intended to bridge the gap between two parallel courses: one based on programming and numerical methods, and the other oriented toward engineering science. The main tasks for the problem in Table 1 were

- *To formulate the design equations to be solved*
- *To determine methods for solving the sub-problems and the overall problem*
- *To plan a set of modules using a spreadsheet and a programming language*
- *To debug and execute the programs*
- *To modify the programs to test different conditions*

Table 2 provides a guideline on the approach and considerations in solving the problem posed in Table 1.

RESULTS

The exercise of "shared course projects" has now been carried out over a three-year period for the first- and second-year courses mentioned above. The problems selected, incorporating components for each course, were relatively large in order to provide a greater challenge than those from

TABLE 2. PIPE NETWORK ANALYSIS—A SOLUTION APPROACH

Solution and Programming Issues (students normally provide full programs and spreadsheets with model equations employed)

- Carry out hand calculation for a single step using the Hardy-Cross Method (*i.e.,* assign signed flow directions to the pipe segment flows and set the sum of flow rates in each loop as zero).
- Choose the guessed values of flow rates in all pipe segments by mass balances.
- Include the Colebrook (or similar) and Hagen-Poiseuille equations for calculating pipe friction losses. Check for flow-regime and use the appropriate equations.
- Include pipe expansion-contraction losses at each junction and the pipe fitting losses.
- Use a local Newton or bisection method for solving the implicit Colebrook or similar equation.
- Develop a flow chart showing the sequence of computations.
- Input the program in modules; test and debug the program at each stage.
- Use comments to make programs readable.
- Carry out one computer iteration and compare with hand calculations.
- Implement full iterative computation for all loops. Modify and test various cases.
- Print out results.

Summary of Analyses and Discussions (students normally provide numerical answers and analyses)

1. Iterative solution is necessary in order to obtain a converged solution because, even though mass is conserved for an initial guess, the sum of head loss around each circuit is non-zero. The converged solution will ensure that mass is conserved and a zero net head loss is obtained within each of the flow circuits.
2. A problem with multiple pipes requires more iterations because in a multiple-pipe circuit, some pipes participate in more than one circuit, and consequently head and flow corrections from more than one circuit need to be applied until the flow rates are balanced.
3. If all pipe diameters are doubled in size, the converged flow rates in each pipe would approximately remain the same. The small differences in converged flows are due to the fact that the head losses computed are not linear with respect to the pipe diameters.
4. The final solution should be insensitive to the initial guess. The solution should be unique.
5. If all the flow rates into and out of the system were increased by 10%, all the other flow rates in the system would increase by approximately 10%. Small discrepancies are due to the nonlinearity of the equations.
6. If the pipes were all smooth, friction factors would be less for a given Reynolds number; hence the head losses would be less. Thus, flow rates would be slightly different because the head loss dependence is nonlinear with respect to pipe roughness.
7. The connection of a supply pump and of outgoing flows will require setting up head-loss equations in an outer loop and incorporating the flow resistances of the associated piping and connected devices. After the inner-loop flow computations are balanced, calculations must be carried out for the outer loop, including the pump performance characteristics, to satisfy the constraints provided. Any flow excess or deficit must be balanced along with the inner-loop flow distributions and solved iteratively.

a single course. A side benefit of the shared project was that the combined time and effort provided by the lecturers and tutors for the two courses helped optimize the total input, and no additional time allocation was needed.

The students found the problems challenging and stimulating, but not overwhelming. The groups functioned better than satisfactory in achieving their objectives and few conflicts were noted. Conflicts related to communication were resolved through encouraging the students to make contact by phone and/or e-mail. Lack of responsibility by any individual was penalized through a lowering that individual's grade. The fact that group members needed to cooperate for a common goal engendered a sense of belonging and a degree of independence and responsibility throughout the project. Our experience indicates that the majority of the teams functioned without major complaints, knew what the other team members were doing, and displayed a satisfactory level of understanding.

The levels of difficulty were not the same for the projects. For some projects the students had to select an appropriate computing tool. In such cases, about two-thirds of the groups opted for the spreadsheet, while a third opted for FORTRAN. For the project described above, no such choice was provided, and the groups were required to set up both a spreadsheet and a program. The groups typically divided the tasks among themselves to concentrate on particular aspects of the problem and then combined efforts on the more difficult parts.

The student experiences indicated varied styles of learning and degrees of expertise in using these tools. A majority of the students were found to be competent in using one of the techniques, while only about a third was proficient in using both. The exercise also highlighted the strengths and weaknesses of the tools used. The spreadsheet was faster in presenting results and was relatively easier to debug but it provided less flexibility and was tedious for variable definition and usage. Developing a program required greater discipline and effort, but was more flexible for experimenting and when it worked, it was more satisfactory in terms of the learning experience.

A majority of the students noted that the project usually took on a life of its own. They also said that it helped them gain an understanding of how their fellow students think and work: "I not only got to know how I think and solve problems, but I also realized the false steps taken and assumptions made by my partners." The students also gained first-hand experience on how to cope with deadline pressures and peer review.

The students spent more time on the project than they anticipated, expressed satisfaction on completing the project, and considered it a memorable experience. Feedback from course evaluations showed improved satisfaction with the courses (about ten to fifteen percent greater satisfaction ratings were noted). Carry-over from the experience to subsequent years was noted in the form of better appreciation of the principles learned from computation and fluid mechanics. Apart from this improvement in carry-over to subsequent years, anecdotal evidence from written course assessments suggests that more students learned more individual course material than before and better understood the relationship between the integrated courses than previous students who experienced a more compartmentalized approach to teaching.

Traditionally, early engineering courses are taught without invoking a major project, sometimes involving only a minor project with limited time and resources. With pooled resources and more challenging projects to offer, the mechanism described has the potential of achieving better results than the traditional approach. In addition, teaching and learning tend to be more rewarding and enjoyable due to the higher degree of interaction between participants with efficient use of resources.

The exercise provided a mechanism to synergize greater curriculum integration, minimize compartmentalization, strengthen cross-disciplinary learning, and reduce student anxiety in meeting submission deadlines for two different courses. The distributed learning process also encouraged variations in approach and ways of learning, such that the students were not subjected to a single prescribed mode throughout. The format of these projects could also be derived from a larger research project to enhance the challenge and to permit the direct flow of research work into teaching.

CONCLUSIONS

Tackling challenging problems with group-based learning can foster deep learning and understanding within the discipline during the formative stages of education. The integrative learning experience can help in the following aspects:

- *It provides students with the option of being involved in structuring their own learning experience*
- *Teachers act as mentors, facilitators, and resource persons rather than as dispensers of information*
- *Teachers discipline and interrupt students less and are less constrained by a lack of time*
- *Students develop both initiative and the skills needed to work cooperatively with their peers*
- *The format assists in developing communication skills*
- *The projects encourage and enable students to critically evaluate their own and each other's work*
- *Students develop confidence in tackling challenging problems*
- *Less able students have the opportunity to reach the competency level of their peers*

Through positive intervention in encouraging reconciliation between courses, we may avoid the ill effects of compartmentalizing courses and help integrate the acquired knowledge of our discipline. Research on cooperative learning is summed up succinctly by Wells, et al.:[7] "...to achieve most effectively the educational goal of knowledge construction, schools and classrooms need to become communities of literate thinkers engaged in collaborative enquiries."

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INTEGRATING PROCESS SAFETY

Continued from page 203.

- *Best-practice databases (e.g., for an ethylene plant, what controls, procedures, and training are adequate)*
- *Methodology to determine time-concentration effects of various toxic materials and combination of these materials*
- *Computational methods for determining fire resistance of structural components in process facilities*

IDENTIFYING PROBLEMS AND MULTIDISCIPLINARY APPROACH

Universities solve problems identified by researchers or industry. For an applied engineering field such as process safety engineering, the problems are usually identified by industry. The approach is to develop effective mechanisms for getting industry input and then taking a multidisciplinary approach to solve the problem. To address the latter, the Center has assembled a highly qualified team of experts who have international reputations in fields ranging across reaction engineering, inherently safe design, numerical analysis, system and equipment reliability, applied probability, organizational structure and planning, non-destructive evaluation, experimental fracture mechanics, materials testing, risk assessment, exposure assessment, cost-benefit analysis, and other areas of expertise.

The vehicle used to identify problems is based on two factors: first, the Center actively seeks input from industry in identifying process safety engineering problems that the Center can help solve, and second, an annual symposium "Beyond Regulatory Compliance: Making Safety Second Nature" is a vehicle to generate ideas and to identify problems.

CONCLUSIONS

In response to the changing role of chemical engineering, chemical engineering departments must adjust and modify their approach to education and research. The education must include a comprehensive exposure to core courses integrated with process-safety problems as well as a limited number of specific process safety engineering courses. Chemical engineering departments must also produce an appropriate number of MS and PhD graduates whose degree programs are focused on process safety engineering problems. Also, to help our graduate students transition into industry, the research we conduct should help industry in a practical and immediate manner. This can be ensured by seeking adequate input from industry as well as other stakeholders.

Public perception of the process industry is significantly affected by process plant accidents. The significant societal role played by industry is largely overlooked when catastrophic accidents occur. The best way to change that perception is through adoption of proactive programs by both industry and universities.

ACKNOWLEDGMENTS

The authors acknowledge the support provided by the Mary Kay O'Connor Process Safety Center and the Chemical Engineering Department at Texas A&M University. They also thank colleagues at Texas A&M University for discussions and research that assisted in the evolution of the ideas and concepts presented herein.

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ACETONE PRODUCTION FROM ISOPROPYL ALCOHOL

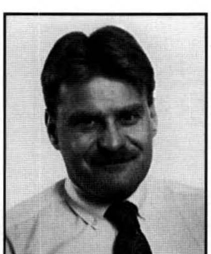
An Example Debottlenecking Problem and Outcomes Assessment Tool

JOSEPH A. SHAEIWITZ, RICHARD TURTON
West Virginia University • Morgantown, WV 26506-6102

Chemical engineering educators are searching for outcomes assessment measures to incorporate as assessment-plan components in order to satisfy the requirements of ABET EC 2000. Student and alumni questionnaires are always a staple, but an assessment plan should not rely too heavily on these self-assessment instruments. Faculty evaluation instruments are also necessary.

All chemical engineering programs have capstone experiences such as the unit operations lab and chemical process design. In these courses, students are expected to apply knowledge learned earlier in the curriculum to solve complex problems. The capstone design experience presents an excellent opportunity for outcomes assessment since it requires that material from several classes be synthesized and applied. It can provide detailed information on what seniors have learned in their earlier classes. In this case, student assessment of the capstone design experience is being used as a program-assessment measure. In particular, the technical content of the capstone design experience can provide data on EC 2000, Criterion 3, outcomes a, c, and e (ability to apply knowledge of mathematics, science and engineering; ability to design a system, etc.; ability to identify, formulate, and solve engineering problems).[1]

Joseph A. Shaeiwitz received his BS from the University of Delaware and his MS and PhD from Carnegie Mellon University. His professional interests are in design, design education, and outcomes assessment. He is co-author of the text Analysis, Synthesis, and Design of Chemical Processes, *published by Prentice Hall in 1998.*



Richard Turton received his BSc from the University of Nottingham and his MS and PhD from Oregon State University. His current research interests are focused in the area of fluidization and its application to the coating of pharmaceutical products. He is co-author of the text Analysis, Synthesis, and Design of Chemical Processes, *published by Prentice Hall in 1998.*

One key to using the capstone design experience for outcomes assessment is the measurement method. For over twenty-five years, seniors in chemical engineering at West Virginia University have been required to do a series of projects in the two-semester senior design course, to submit a written report, and to defend their results to an audience of at least two faculty. A typical defense lasts one hour, with a fifteen- to twenty-minute presentation followed by a question-and-answer session. Students do these projects and defend them individually, which is a unique feature of our curriculum. The question-and-answer period is tantamount to an individual tutorial. Students get immediate feedback on their work and faculty can determine in great detail the level of each student's understanding of and ability to apply fundamental principles. Historically, students were not permitted to ask questions of anyone while doing this assignment, but in recent years, they have been permitted to buy consulting from faculty for a minor grade deduction. This system ensures that students ask only well-formulated questions and that they do not try to "nickel and dime" a solution from faculty.

Oral examinations like this have advantages and disadvantages as an outcomes assessment measure.[2] The advantages include an ability to measure student learning in great detail through follow-up questions. Faculty can learn how and why students obtain their results and develop an understanding of students' thought patterns. This makes it easier to determine if a reasonable result was obtained by accident from a series of unreasonable procedures. Additionally, the immediate student feedback is an excellent learning experience. Oral and written communication skills are also developed. The major disadvantages to this method are the faculty time required and the potential for student intimidation.

In this paper, the production of acetone from isopropyl alcohol (IPA) is used as an example. The assignments are described, followed by a brief summary of the issues involved in the problem's solution. Then, a typical series of questions asked of students and how learning is assessed through the responses to these questions is discussed.

THE PROBLEM

Figure 1 is a process flow diagram for the production of 15,000 tonne/y acetone from IPA. Most of the world's supply of acetone is produced as a by-product of reacting cumene to phenol via the cumene hydroperoxide process. Acetone used for pharmaceutical applications, however, is sometimes produced from IPA due to the requirement of zero aromatic impurities. The problem assigned is one of debottlenecking. As will be discussed later, the ability to use this process for assessment purposes is independent of whether a traditional process design, debottlenecking, or troubleshooting is involved in the assignment.

The assignment scenario is that a company has designed this process to produce 15,000 tonne/y of acetone and equipment has already been ordered. The process was designed assuming an 8,000-hour year, but it has now been learned that the process is to produce the desired yearly amount of acetone in 6,000 hours, allowing the equipment to be used to produce another product for the remainder of the year. Therefore, a method to scale the process up by 33% must be found at minimum equipment cost, particularly for special-ordered equipment that cannot be returned to the vendor for replacement.

This problem was assigned in two parts. The first part was to analyze the process up to T-401, the acetone scrubber, and the second assignment was to implement heat integration between the reactor effluent and the reactor feed (more details later) and to analyze the second distillation column, T-403. Students were given equipment specifications, some design calculations, and stream and utility flow tables. Much of this information is available elsewhere,[3,4] and interested faculty can contact either of the authors for additional information. It should be noted that prior to these assignments, our students receive significant instruction on analysis of performance problems, *i.e.,* problems in which the equipment and input is specified and where the outlet conditions must be determined.[5]

THE DEBOTTLENECKING PROBLEM

A brief summary of the debottlenecking problem is presented here. This information in incomplete and descriptive in nature. It is presented to provide background for the discussion on assessment.

System Pressure Drop The details of the problem statement make it clear that the ideal scale-up situation is for the input to the separation vessel, V-402, to be at the same temperature and composition as in the original design, just at a higher flowrate. This fixes the pressure entering the vessel. It is stated that pressure drop in the pipes is negligible;

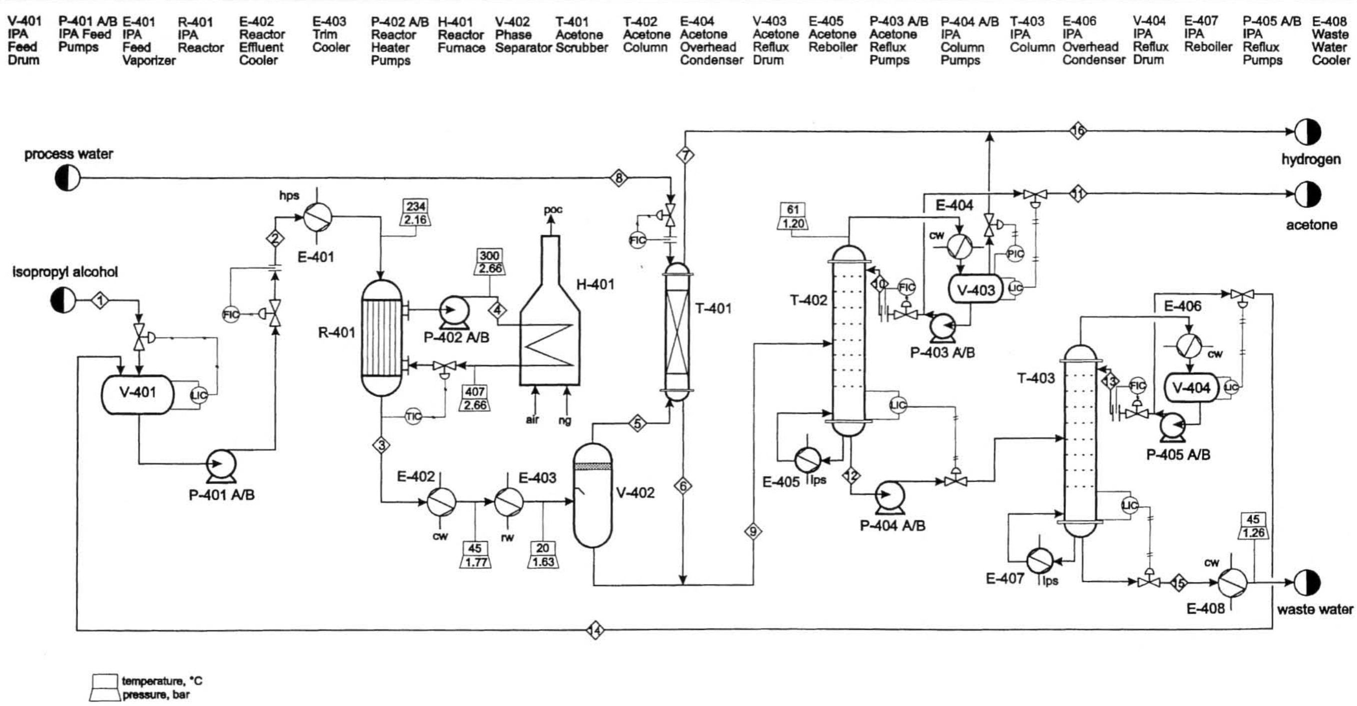


Figure 1. *Process flow diagram for acetone production from isopropyl alcohol. Stream numbers refer to Stream Table in Reference 3.*

therefore, at the increased flowrate (assuming incompressible flow) the pressure drop through certain pieces of equipment increases by a factor of 1.33^2. For gas flows, the effect of pressure on density and its effect on the pressure drop can also be included, but a trial-and-error solution is required. At the specified scale-up, the pressure drop in the fluidized bed reactor is constant. The result is that the front end of the process is pressurized relative to the original design. Each piece of equipment has a maximum allowable working pressure that must be checked at the scaled-up design.

Feed Pump A pump curve and a curve showing the net positive suction head required by the pump ($NPSH_R$) curve are provided for P-401 A/B. The system curve must be plotted with the pump curve to determine if the maximum allowable flowrate has been exceeded. If so, remedies such as running both pumps in parallel (and ordering another spare) or attempting to exchange these pumps for ones generating more head are possible. If the former solution is chosen, it must be determined if there is sufficient NPSH available for the new suction-side flow.

Heat Exchanger E-401 The effluent from this heat exchanger is saturated vapor. The steam temperature, and hence the steam pressure, must be increased to accommodate the increased flow. Since the outlet pressure increases, the outlet temperature also increases.

Reactor The reaction is endothermic. In the reactor, energy is supplied by molten salt heated in the fired heater. The fired heater only has 10% additional capacity. The simple solution is to purchase an additional fired heater. A more elegant solution is to use the reactor effluent at 350°C to preheat the reactor feed, which can lower the heat duty on the fired heater, even at scaled-up conditions. The fluidized bed has about 50% inert filler, so the fraction of active catalyst can be increased to handle the increased throughput. But the amount of additional active catalyst required is much less than 33% since the space velocity decreases at the increased reactor pressure.

Molten Salt Loop The performance of the molten salt loop must be analyzed correctly to determine the molten salt temperatures entering and leaving the reactor at scaled-up conditions. Both the energy balance and the design equation for the reactor heat exchanger must be solved simultaneously. The two temperatures plus the flowrate of molten salt are unknown. One may be set to solve for the other two. In practice, the flowrate would be controlled and the temperatures would respond to changes in flowrate.

Heat Exchangers E-402, E-403, and E-408 At the new inlet conditions, the outlet conditions must be determined for these three heat exchangers. There is a restriction that cooling water and refrigerated water flowrates can only be increased by 20% due to velocity considerations.

Tower, T-401 The original specification is 1-in ceramic Raschig rings. The tower will flood at 33% increased throughput of both gas and liquid. One solution is to change the packing to 1.5-in ceramic Raschig rings, 1-in Berl Saddles, or 1-in Intalox Saddles. All of these have lower packing factors, and the saddles have similar interfacial areas per unit packing, which would presumably lead to similar mass transfer rates.

Tower T-403 and Peripheral Equipment The tower will flood at 33% scale-up. There are three possible solutions. Because this tower has a small diameter, the trays have been designed as a module to drop into the vessel's shell, so the number of trays can be easily increased if the tray spacing is decreased. This permits the reflux ratio to be decreased and avoids flooding, which is an example of the trade-off between the number of stages and the reflux ratio. But the effect of decreased tray spacing on tray efficiency should be considered. The pressure of the column can be increased if a pump is added after T-402. Increasing the pressure increases the vapor densities, decreasing the vapor velocity and avoiding flooding. Some combination of increased pressure and decreased reflux ratio provides a satisfactory solution.

Perhaps the best solution is just to decrease the reflux ratio. The distillate is a near azeotropic mixture of IPA and water. The original design, as illustrated in a McCabe-Thiele diagram given to students, has more trays than necessary in an attempt to get closer than necessary to the azeotrope. Decreasing the reflux ratio to avoid flooding only reduces the top IPA mole fraction from 0.65 to 0.64! Once the reflux ratio is determined, the reboiler and condenser performance must be analyzed to determine the new outlet conditions. Also, the reflux pump must be analyzed. For cases involving an increase in overhead liquid flow, there may be insufficient NPSH for pump P-405 A/B, but the original design uses very small diameter (0.5 in) suction and discharge lines. Increasing the diameter of these lines to 0.75 or 1 inch easily lowers the friction since the pressure drop is inversely proportional to d^5.

It should be noted that all aspects of basic chemical engineering are included in this project. This is desirable when a process such as this is used for program assessment.

ASSESSMENT

Three scenarios of faculty-student interaction during questioning are presented as examples of how projects such as this one can be used for outcomes assessment. All of these scenarios are paraphrased actual responses from several students. The reader should observe how the student receives immediate feedback on results presented.

The first example is the absorber, T-301. The student has presented the solution of increasing the water rate by 33% to handle the same increased rate of gas to be scrubbed. The student also suggests changing the packing from 1-in ceramic Raschig rings to 1.5-in ceramic Raschig rings because the decrease in packing factor allows the column to remain below flooding. Consider the following exchange between student and professor.

Professor *Why did you increase the water flowrate by 33%?*

Student *To maintain the same liquid-to-gas ratio so I could get the same separation.*

Professor *Why did you go to 1.5-in Raschig rings?*

Student *Because the packing factor is smaller. This lowers the y-position (ordinate) on the flooding graph enough so the column will not flood at the increased gas flowrate.*

Professor *What about the interfacial area of the new packing?*

Student *I really did not think about that.*

Professor *Well, let's think about it now. What happens to the interfacial area?*

Student (stumbles around for an answer)

Professor *What has a smaller surface area per unit volume—a bed packed with sand or a bed packed with marbles?*

Student *Marbles. So, I guess the surface area decreases with larger Raschig rings.*

Professor *Will this have any effect on the absorber?*

Student *Yes, it will have an effect.*

Professor *OK. Will it help or hurt the separation?*

Student *It will probably decrease the separation.*

Professor *Correct. So, what would you now have to do to maintain the desired separation?*

Student *Well, I would increase the water rate more.*

Professor *Would this cause the column to flood?*

Student *I'm not sure since I did not do this calculation.*

Professor *Well, what is the trend?*

Student *Increasing the liquid rate would increase the x-position (abscissa) on the flooding graph, which moves the column toward flooding.*

Professor *OK. Let's assume that flooding again becomes a problem. What else could you do to maintain the desired separation without increasing the water rate?*

Student (stumbles around for an answer)

Professor *Let me ask the question differently. What else can you change to make the separation easier? What will increase the affinity of the acetone for the water?*

Student *Oh. The pressure and temperature could be changed.*

Professor *In what direction?*

Student *Let's see. Lower temperature and higher pressure favor the liquid phase.*

Clearly, this student understands most everything one would expect a student to understand about absorbers, but the presentation of the student's solution alone does not reveal this fact. It only becomes clear as a result of the question-and-answer session. When this problem was assigned, increasing the size of the Raschig rings was the most common solution. Very few students proposed using larger Berl or Intalox saddles, which have similar interfacial areas to small Raschig rings. Upon questioning, the better students immediately understood the problem and responded as illustrated above. When students have trouble answering a question, as in the case above on packing area and other ways to maintain the desired separation, the question is always rephrased in such a way as to provide a hint for the student.

This type of faculty-student dialog can reveal situations in which a student arrives at a good solution without fully understanding the reasons why it is a good solution. The following is an example from a solution to scale up T-403.

Student (proposes lowering the reflux ratio in T-403)

Professor *How did you arrive at the solution of only lowering the reflux ratio?*

Student *I did the simulation on Chemcad and found that I could lower the reflux ratio without really affecting the distillate or bottom mole fractions.*

Professor *Based on what you learned in separations, does this make sense?*

Student *I didn't think about it. I assumed the simulation results were correct.*

Professor *They may well be correct, but we need to understand why. So, does it make sense that lowering the reflux ratio with the same feed and the same number of trays does not affect the outlet concentrations?*

Student *No, I would expect the separation to be worse.*

Professor *So, what is special about this case that allows the separation to be maintained at the lower reflux ratio?*

The discussion now continues as the student is shown the McCabe-Thiele diagram, which was provided with the assignment but apparently ignored. This reveals that the original column was overdesigned. There are several stages approaching the azeotrope that provide very little incremental separation. Therefore, fewer stages at the top or lowering the reflux ratio do not appreciably affect the distillate concentration.

Once again, only the question-and-answer session reveals that a correct solution was presented without in-depth analysis, perhaps without a detailed understanding of the reason why the solution was correct. Both situations illustrated above are examples of how student learning can be assessed while students are simultaneously provided with individual feedback on their work. It is a win-win situation.

The following is an example of dialog when an incorrect solution is presented. In this case, the student has attempted to draw the system curve on the pump curve graph (which is provided) for the reflux pump, P-405 A/B, to determine if the pump has sufficient head to handle the increased overhead liquid flowrate for a solution that involves replacing the existing trays while maintaining the same reflux ratio.

Student (Presents Figure 2; claims that doubling the diameter of the suction and discharge lines is not sufficient to operate at the scaled-up conditions and suggests purchasing a new pump with a more favorable pump curve or running both pumps in parallel and purchasing another spare.)

Professor *I do not understand your pump and system curve analysis. Please explain it to me.*

Student *The pump curve was supplied. I plotted the system curve. Since the desired flowrate is larger than the point at which the two curves intersect, the existing pump does not supply sufficient head at the desired flowrate.*

Professor *From what we did in class, does it make sense that there is so little effect of pipe diameter?*

Student *I didn't think about that. I did the calculation just like we did it in class, and this is what I got.*

Professor *Let's try to analyze this in more detail. What relationship does the system curve represent?*

Student (stumbles around, cannot generate the desired relationship)

Professor *The system curve has an intercept. What does this represent physically?*

Student *Oh. Isn't that the static pressure difference?*

Professor *For this case, yes. Now, what else causes pressure drop?*

Student *Friction.*

Professor *And, what part of the curve represents the frictional pressure drop?*

Student (stumbles around for an answer)

Professor *What is frictional pressure drop most significantly dependent upon?*

Student *Velocity.*

Professor *Where is velocity represented on the graph?*

Student *Ummm. Oh. It is in the flowrate on the x-axis.*

Professor *OK. So how is frictional pressure drop related to flowrate or velocity?*

Student *It goes with velocity squared.*

Professor *OK. So how is this shown on the graph?*

Student *It is in the parabolic shape of the graph.*

Professor *OK. So we now know that the intercept of the graph is the static pressure change, and the curvature of the graph is related to the frictional loss. So, let's look at the frictional pressure drop. Let's pick the point on the original (0.5-in) system curve for your scaled-up flowrate. What happens to this point if the diameter of the suction and discharge lines are doubled?*

Student *It should be lower on the y-axis.*

Professor *Which you show on this graph. However, how much lower should it be?*

Student *Well, this is what I got.*

Professor *If you increase the pipe diameters, what does that do to the friction?*

Student (stumbles around for an answer)

Professor *What is the relationship for frictional pressure drop? Do you remember it?*

Student (Writes the equation $\Delta P = 2\rho f L_{eq} v^2 / d$ on the board, perhaps with some assistance. Most students know the square relationship on velocity and the inverse relationship on d, but not all can remember all of the other terms.)

Professor *So, what happens to the frictional pressure drop if the diameter is, for example, doubled?*

Student *It is half the original value. This is what my graph shows.*

Professor *Yes, that is what your graph shows, but are you sure that you have the correct relationship? Does anything else in that equation change if the diameter is doubled?*

Student *Oh. The velocity decreases. I guess I forgot to consider that.*

Professor *By how much does it decrease:*

Student (Figures out from $\dot{m} = \rho A v$ that velocity is inversely proportional to d^4, so that the frictional pressure drop is inversely proportional to d^5. Assistance and coaching may be required.)

Professor *So, if the diameter is doubled, by how much does the frictional pressure drop decrease?*

Student *Let's see. By a factor of two to the fifth. That's 32.*

Professor *So, if the frictional pressure drop decreases by a factor of 32, how does this affect the graph?*

Student *The y-axis value decreases by a factor of 32.*

Professor *Are you sure? Remember the intercept.*

Student *Oh. The difference between the intercept and the y-value decreases by a factor of 32.*

Professor *So, what does that do to the system curve?*

Student *It will be almost flat. So I guess the existing pumps will work after all if the pipe diameters are doubled.*

This exchange is an example of the tutorial nature of the interaction. An erroneous result is analyzed, via careful questioning, to lead the student to a correct result. Through questioning and coaching, the student "independently" discovers the error made and determines the correct result.

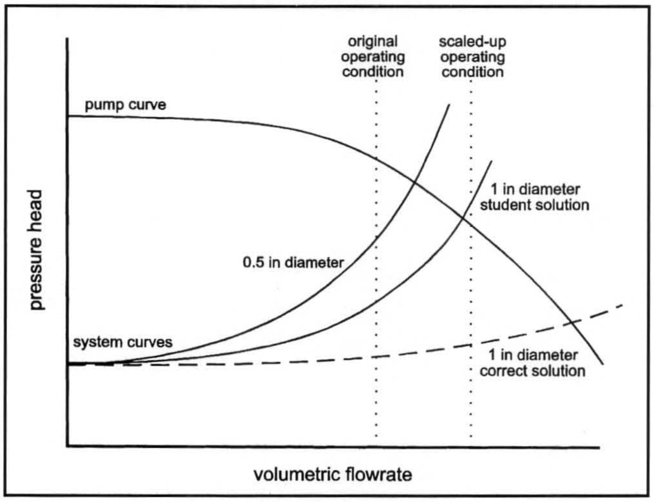


Figure 2. *Sketches of pump and system curves for P-405. Solid curves are student result; dashed curve is correct calculation for larger pipe diameter.*

USING ASSESSMENT RESULTS—CLOSING THE LOOP

Assessment results from this exercise are used in several different ways, all of which "close the loop" on the assessment process. The one-hour presentation and question period provide students with immediate feedback. After all of the presentations have been completed, class time is devoted to project review. One or two of the best projects are presented. Faculty review the problem, noting areas where better solutions could have been presented. Follow-up problems are usually assigned. Sometimes these are assigned only to individuals, *i.e.,* to students who did not do them correctly on the project. In the case of this acetone problem, the heat integration option was ignored by most student on the first project. Therefore, it was assigned specifically on the second project.

An assessment report following each project is also prepared and circulated to all faculty. It describes the project, what types of solutions were expected and what types were actually submitted. Areas where a significant number of students did well are pointed out. For example, if a majority of students responded to questions about T-401 as the student in the example did, this would be specifically stated. Areas where a significant number of students were found to be deficient are also pointed out—if a number of students did not think about the meaning of process simulator results, simply accepting the results on faith, or if a significant number made the error regarding frictional losses, this would be specifically cited. In these cases, remedies to ensure that future students are not deficient in the same area are suggested. Faculty are expected to respond to the suggestions. Do they? In general, our faculty do because of our culture supporting these projects and due to the pressure we all feel not to have material we taught show up as being deficient on these projects.

IMPLEMENTATION SUGGESTIONS

Outcomes assessment using oral presentations of capstone projects can be implemented by making only minor changes in how typical design classes are run. First of all, it is not necessary to use a performance (debottlenecking or troubleshooting) problem such as the one described here, although such problems lend themselves to this type of assessment process. Since our students enter the senior year having already completed a process design during their sophomore and junior years,[6] they are prepared for this type of assignment. Asking probing questions in a typical capstone design project can yield the same type of assessment information. The best questions to ask are "why" and "what if." For example, ask why the column was designed for a specific reflux ratio. Was it chosen *ad hoc,* or was it based on an optimization of the trade-off between number of stages and reflux ratio? What if scale-up is required in the future? Similarly, why were the reactor temperature, pressure, and/or conversion chosen at the specified values? Were they merely convenient values? Or, was the selectivity analyzed to determine conditions that maximize profit?

It is also not necessary for students to do projects individually for the presentations to be used for assessment purposes. To implement this in a group of 3-5 students, interim progress reports (which can be informal) are suggested. Students can make a brief presentation to either a professor or a TA (who would need some training in what to look for and how to ask questions), and the students would then be expected to respond to questions. Questions should be directed to individual group members to avoid domination by one person. The assumption should be that any student is prepared to respond to any question, not just to the material presented by that student. If a student is unable to respond, then another student can be chosen or the question could be answered by a volunteer. Assessment information would be gathered and students would get feedback on their project while it is in progress, which would probably improve the final product.

A project review is also desirable to close the assessment loop. This should be done after all presentations have been completed, preferably after all project reports have been graded.

CONCLUSION

Performance problems such as the debottlenecking problem illustrated here are a rich opportunity for outcomes assessment, as are process design problems. Asking "why" and "what if" type questions probes students' understanding of fundamental principles. The oral presentation format provides students with immediate feedback, closing one feedback loop. Another way to close the assessment loop is by project assignment review in class and/or follow-up assignments. Feedback to faculty regarding students' ability to apply the principles they are expected to understand closes another feedback loop. The only real disadvantage is the investment in faculty time for the oral presentations. If it is believed that outcomes assessment and EC 2000 will result in increased faculty time devoted to the undergraduate curriculum, a key choice is how to invest this time. Questioning students in oral presentations of capstone projects is one potentially beneficial way to invest that time.

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SEQUENTIAL BATCH PROCESSING EXPERIMENT

For First-Year ChE Students

Ronald J. Willey, J. Anthony Wilson,* Warren E. Jones,* John H. Hills*
Northeastern University • Boston, MA 02115

Batch and semicontinuous operations are often used within the chemical process industries. For example, the pharmaceutical, food, consumer products, and pulp and paper industries regularly use batch processing. Also, many chemicals are made on a semicontinuous basis. According to a recent AIChE survey of the entry-level job market, 60% of recent chemical engineering graduates are entering industries that use either batch or semicontinuous operations.[1] Yet the engineering curriculum devotes less than 10% of its instructional time to batch or semi-continuous operations. Further, if chemical engineers are making an impact in the area of industrial batch and semicontinuous processes, then it seems logical to introduce chemical engineering students to those operations early in their education.

THE UNIVERSITY OF NOTTINGHAM

The University of Nottingham is located in the Midlands of Great Britain about 120 miles north of London. The total University enrollment is approximately 18,000 undergraduate and 3,500 graduate students. Chemical engineering is part of the School of Chemical, Environmental, and Mining Engineering. The School's enrollment is about 400 students, divided between courses in chemical, environmental, and mining engineering, undergraduate (3-year BEng and 4-year MEng**), and postgraduate (taught MSc and research MPhil, PhD). In Great Britain, most university entrants have A-level, which is equivalent to two years of preparation beyond the high school degree.

As shown in Figure 1, the chemical engineering laboratory at the University of Nottingham is impressive even by United States' standards. The operating laboratory floor space is 128 by 32 feet (4,096 ft^2) and has a 27-foot-high ceiling to accommodate tall equipment. There are five additional laboratories (approximately 1,000 ft^2 each) located on both sides of the main laboratory.

The University of Nottingham laboratory has a substantial support staff, with one chief technician in charge of four

** Address: University of Nottingham, Nottingham, Nottinghamshire, Great Britain NG7 2RD*
*** Students arrive at Nottingham after a 2-year curriculum similar to US freshman and portions of a sophomore college-level curriculum. BEng and BS are similar curricula. MEng is similar to a MS Chem Eng.; however, the equivalent thesis component, listed as a research or design project, leans more toward application and advancement of current engineering practices.*

Ronald Willey *holds a BS from the University of New Hampshire and a PhD from the University of Massachusetts (Amherst). He joined the Northeastern faculty in 1983. His teaching centers around the unit operations laboratory and his interests include integration of process safety into the chemical engineering curriculum. He is a registered engineer in the Commonwealth of Massachusetts.*
Anthony Wilson *holds BSc and PhD degrees in chemical engineering from the University of Nottingham. With industrial and consulting experience in process control and batch process engineering, and active research in both fields, he coordinates the school's research in computer-aided process engineering.*
Warren Jones *holds BSc and PhD degrees in chemical engineering from the University of Nottingham. He has a wide-ranging interest in both front-end process and detailed plant design, developed initially through nine years of experience with a major engineering and construction company. Teaching responsibilities include several plant design courses and engineering thermodynamics.*
John Hills *holds MA and PhD degrees from the University of Cambridge. He worked in industrial R&D and taught in Africa before coming to Nottingham. His research interests are in gas-liquid reactors and multiphase flow, and he currently teaches chemical reactor design and chemical thermodynamics.*

machinists, one electronics technician, and two full-time laboratory technicians who prepare experiments and watch students during lab operations. Two or three graduate students are also present during any particular laboratory day. Typically, ten to fifteen groups, composed of two or three students each, are in the laboratory on laboratory days (Tuesday and Thursday afternoons). Typical hours are from 2:00 to 4:30 P.M., but several experiments take longer.

The laboratory experience encompasses the first three years of Nottingham's chemical engineering course. Usually, experiments during a particular semester follow the chemical engineering lecture class schedule.[2] First- and second-year students spend approximately five sessions per semester in the laboratory, and the third-year students spend two sessions on process control experiments. Those students who elect to take the BEng spend an additional five sessions working on a large unit operations experiment such as vacuum distillation, crystallization, liquid-liquid extraction, or filtration. These comprehensive experiments serve as term projects, and generally, one or two full-time faculty are present in the laboratory during a session. During the spring semester, the third-year MEng students are in the laboratory in place of the BEng for the term projects.

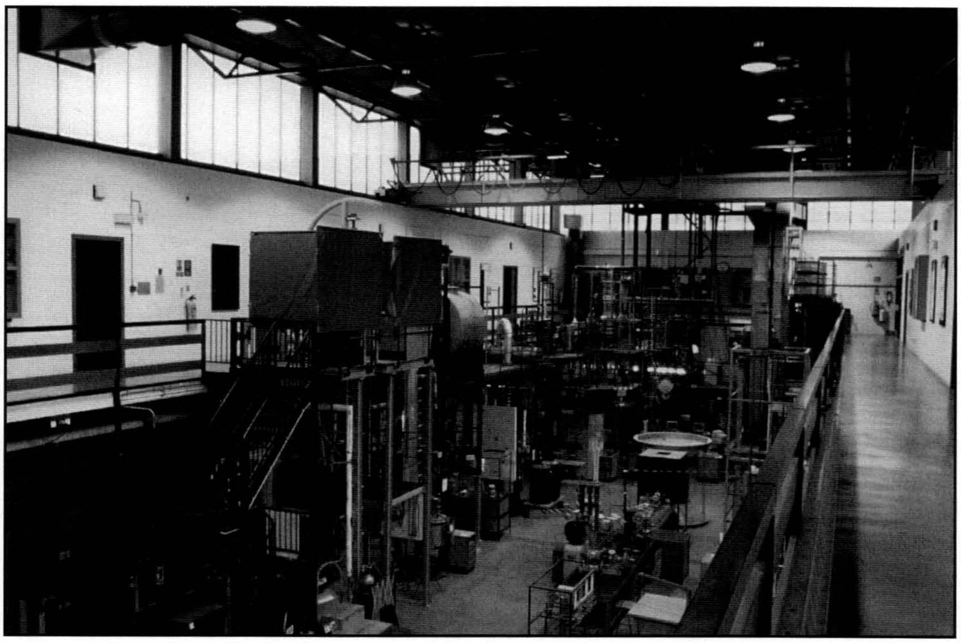

Figure 1. *Nottingham's unit operations laboratory.*

. . . students are able to experience process equipment on a scale similar to that which they will encounter in industry. Observing and operating such a rig has no bench-scale substitute.

As mentioned above, experimental work is done continuously throughout the student's university career. The first-year students do simple experiments such as flow through pipes, flow through orifices, flow through pipe systems, velocity profiles, measurements of heat transfer coefficients, and mass/energy balances. These experiments are done concurrently while the students are taking lecture courses in fluid mechanics, heat transfer, and mass/energy balances. For example, the sequential controlled-batch plant experiment is performed by first-year students who are also taking the basic chemical-process principles course. The purpose of this brief summary is to allow the reader to make a rough comparison between U.S. and UK degree schemes. Grose provides a broader perspective on engineering education in the UK.[3]

FRESHMAN/FIRST-YEAR EXPERIENCE

There is renewed interest in introducing students to engineering concepts through hands-on experience. Many efforts, with good reason, are at bench scale. One example is the work of Hesketh,[4] which includes the reverse engineering of a coffee maker (conceived while a post doc in Great Britain). Another effort is the ongoing work by Perna and Hanesian[5] at the New Jersey Institute of Technology. They have taken several freshman engineering groups through a set of instrumentation/fluid-mechanics experiments with excellent success. But, again, these experiments are primarily bench scale.

The experiment described in this paper is on a larger scale. It is based around a 400-liter (about 100 gallons) vessel and uses steam at significant pressure (100 psig). Thus, students are able to experience process equipment on a scale similar to that which they will encounter in industry. Observing and operating such a rig has no bench-scale substitute.

DESCRIPTION OF EXPERIMENT

The plant schematic is shown in Figure 2. The metering Tank M is filled with Feed A by Pump P and discharged into process Tank T via Valve A. High- and low-level sensors are provided for both Tanks M and T. Tank T is only partially filled by A, so Feed B is added until a Hi position is reached. At the same time, the agitator starts, and once full, the contents of the tank are heated by steam to 55°C and left for 10 minutes. The tank is then cooled to 40°C and the contents are discharged. Other sensors involved include those for temperature and valve position (open or shut).

The first step in the system design (discussed in more detail later) is to specify the sequence of actions required and then to identify the conditions necessary for a particular action. For example, Pump P operates if Tank M is low and Valve A is closed. To successfully manually operate or automate any batch process, it is very important to fully appreciate the process sequence logic—otherwise valves will be in the wrong position and pumps will be left on when they should be off.

Students were given two objectives for this experiment:

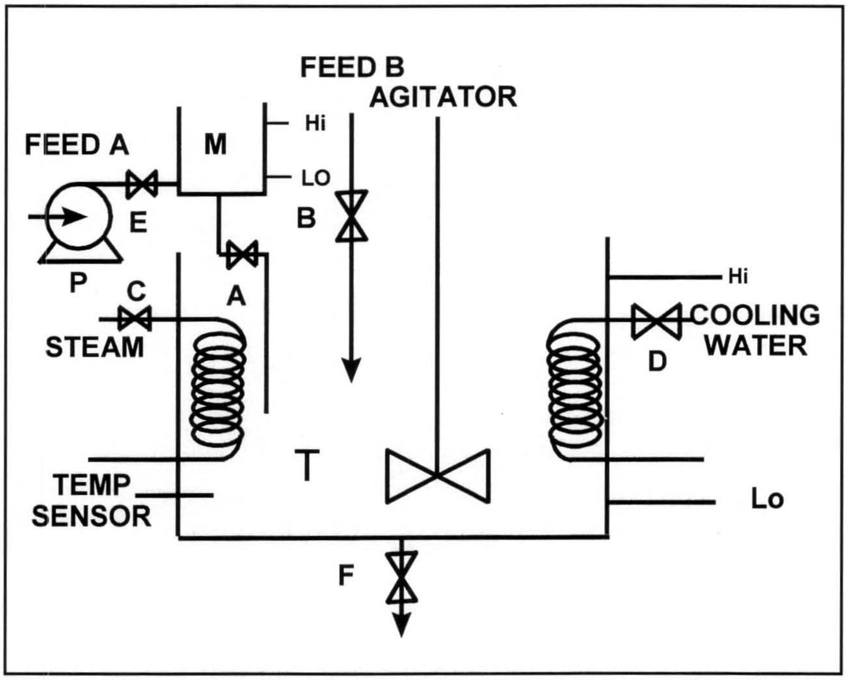

Figure 2. Sequential batch processing experiment schematic.

TABLE 1
Process Sequence

1. Accurately measure quantity of expensive feed stock A charged to the reactor (which is initially empty) from the metering tank.
2. The agitator starts and the reactor is filled to a preset volume with cheaper reactant B. Meanwhile, the metering tank refills, ready for the next cycle.
3. Low-pressure steam is admitted to the jacket surrounding the reactor, and heating stops when the desired "high" temperature is reached.
4. Stirring is continued alone for a set reaction period.
5. Cooling water passes through a coil in the reactor and stops when the desired "low" temperature is reached.
6. Reactor empties and stirrer stops.
7. Cycle completed - ready to start at (1) again.

TABLE 2
Operating Check-List

1. ___	Tank M at Hi level (high-level panel light is on)
2. ___	Tank T at Lo level (low-level panel light is on)
3. ___	Valve A is closed (panel light is off)
4. _x_	Mains water (i.e., B) supply is available
5. ___	Valve B is closed (panel light is off)
6. _x_	Steam supply available
7. ___	Valve C is closed (panel light is off
8. _x_	Cooling water supply available
9. ___	Valve D is closed (panel light is off)
10. ___	Pump P is off (no sound)
11. ___	Valve E is closed (panel light is off)
12. ___	Valve F is closed (panel light is off)
13. _x_	Lower supply reservoir filled with A and ready

____

Signature of Group Member Verifying the Check

If any of these conditions are not correct, notify Prof. Willey or a technician before continuing.

- *To obtain experience with a sequentially controlled batch plant and to gain appreciation of the advantages resulting from automated operation.*
- *To perform heat balances on the heating and cooling operations that form part of the batch cycle.*

To help students understand the process sequence, they are provided with Table 1, which can be read while they follow the automated operation on the control panel. To reinforce the importance of having all components in the correct mode before starting a batch, they also receive a Check-List (see Table 2).

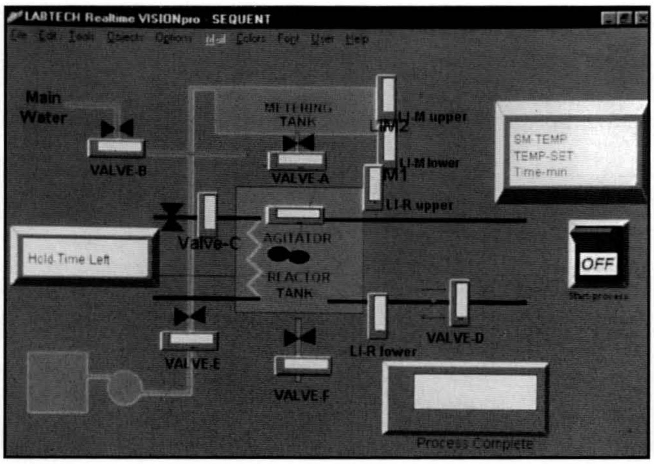

Figure 3. *LabTech Vision™ screen created for automatic control. A mouse pointer is used to initiate the On/Off switch.*

IMPLEMENTATION

This sequence is implemented in two ways. First, the experiment is done under automatic control; the students simply initiate the experiment by moving the on-off switch located on a computer monitor (see Figure 3) to "on," using a mouse. In the second experiment, students implement the sequence and record data manually. They use thermometers, stop watches, and toggle switches located on the computer monitor, as shown in Figure 4.

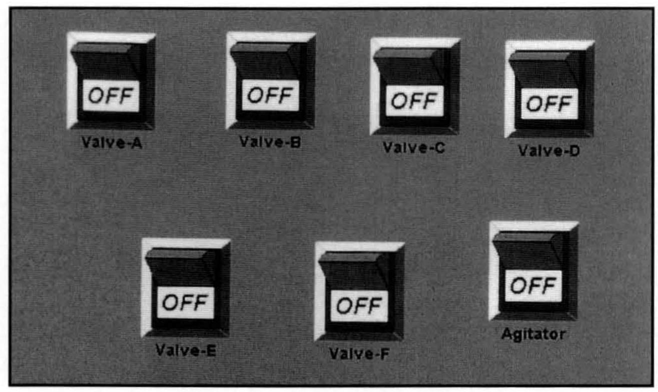

Figure 4. *LabTech Vision™ screen created for manual control. Students use a mouse pointer to initiate the various On/Off switches in correct sequence.*

TABLE 3
Summary of Steps Involved in Sequential Batch Experiments

Step No.	Operation	Proceed on Condition That...	Initiated by	Ended by	Action Necessary
1	• Fill Tank M with Feed A	• Valve A closed	• Tank M low	• Tank M high	• Open Valve E • Start Pump P
2.	• Discharge Tank M to Tank T	• Tank M high • Valve F closed • Valve E closed • Tank T low • Pump P off	• Start: Push Button	• Tank M low	• Open Valve A
3.	• Add Feed B • Start agitator		• Tank M discharged into T	• Tank T high	• Open Valve E • Close Valve A • Start agitator
4.	• Heat to 55°C		• Tank T high	• Temp at 55°C	• Open Valve C • Close Valve B
5.	• Wait for the duration specified		• Temp 55°C	• Timer	• Start Timer • Close Valve C
6.	• Cool to 40°C		• Timer	• Temp at 40°C	• Open Valve D
7.	• Discharge	• Valve A closed • Valve B closed	• Temp at 40°C	• Tank T low	• Open Valve F • Close Valve D
8.	• Process Complete		• Tank T low	• Start of new batch	• Light warning lamp • Stop agitator • Close Valve F

Programming Required to Develop the Experiment

The biggest challenge is programming LabTech Control[6] to operate a batch process. It has the capability to read analog signals, to record data to diskette, and to display data on computer monitors. It also has the ability to perform PID and on-off control.

The analog signals acquired are four level sensors, 0.2 volts when low and 2.5 volts when high. Signals are also acquired from thermocouples reading the batch temperature and the cooling water temperature. The signals sent out are all digital (Hi or Lo). They control the agitator (on or off), the opening of Valve A (which drains Tank M), Valve B (which controls the admission of Feed B to Tank T), Valve C (which controls the admission of steam for heating), Valve D (which controls the admission of cooling water), Valve E (which controls the refilling of Tank A), and Valve F (which controls the draining of Tank T). These valves have to be turned on in the correct sequence for the batch experiment to operate correctly. In LabTech this is done by using two stages triggered by the proper conditions. For example, Stage 1 for Valve A is a 1-Hz stage of 1 second. It is triggered open when the students switch the on-off switch (located on the computer monitor) to "on" by using the mouse. Stage 2 for Valve A is a 1-Hz stage of 7200 seconds (the experiment takes about 3600 seconds) triggered on after the Lo-Level sensor in Tank M indicates that Tank M is empty. When Tank M is sensed empty, Valve A closes and stays closed for the duration of the experiment. Valve B is triggered open (Stage 1) by the same Lo-Level sensor. It is triggered closed (Stage 2) when the water reaches the Hi-Level sensor in Tank T. Table 3 gives the sequence of events programmed through LabTech Control using essentially two stages—one to initiate and one to terminate the desired action.

Desired batch temperatures are read from a data file that is set up beforehand which contain the desired batch temperatures. In this case, the initial set temperature is 20°C (ambient) (a LabTech Stage immediately reading at frequency of 1 Hz and on for only 0.5 second, thus only one point is read). When Tank T becomes full, the high temperature (55°C) setpoint is read when triggered by a Hi signal received from the Hi-level sensor located in Tank T. After the tank reaches this temperature, another LabTech Stage with a frequency of 1 Hz over the hold time (in Hz) is used to read the same temperature (55°C), followed by the lower cooler dump temperature (40°C).

RESULTS ACQUIRED BY STUDENTS

For the first run, data are acquired to ASCII data files by using LabTech Control data acquisition capabilities. Information recorded is: time of sampling event, temperature of Tank T contents, and the outlet temperature of the cooling water. These are acquired at a frequency of 0.0167 Hz (or every minute). For the second run, data are acquired manually by recording temperature every minute into a laboratory notebook. In groups that comprise three students, one student controls the sequence of the experiment while another

Event	AUTOMATED CONTROL (mins)	MANUAL CONTROL (mins)
Valve A Opens	0.15	0.00
Valve A Closes, Valve B Opens + Mixer	1.25	1.08
Valve B Closes, Valve C & E Opens	2.67	2.28
Valve E Closes	3.92	3.92
Temp. reached set point 55 C	13.13	13.33
End of Holding Time (10 Mins), Valve D Opens	23.15	23.37
Valve D Closes, Valve F Opens	32.90	37.50
Valve F Closes	42.55	46.50
END	42.57	46.50

Figure 5. *Event times reported by a student for the two experiments: automatic and manual control.*

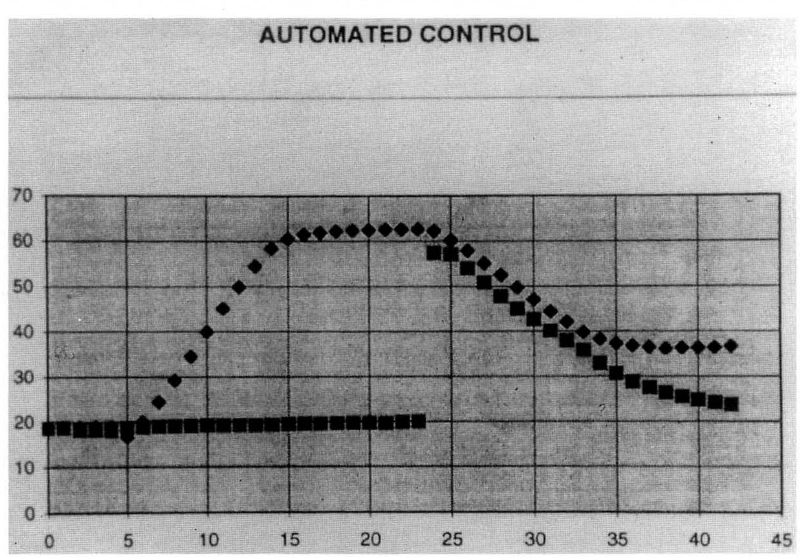

Figure 6. *Temperatures, °C, acquired by Lab Tech as a function of elapsed times, mins, as presented in a student's report.*

student records temperature data, and the third student collects steam condensate, calibrates the rotameter, and monitors cooling water flow through the rotameter.

Figures 5 and 6 are results taken from a student report. Figure 5 shows timed events for the two methods of operation. In this case, the student noted in his report that the automatic control was faster (by about 10%) and therefore manual control is less efficient, and that over time this would equate to a 10% decrease in production rate.

Figure 6 shows a very smooth temperature profile acquired by LabTech Control and later plotted by the student using Microsoft Excel. Series 1 represents the batch temperatures (in Tank T), and Series 2 represents the cooling water outlet temperature. We see that it took about ten minutes to heat the batch to 62°C (set point was 55°C—on/off control was used in this case) and that the batch held at this temperature for the required ten minutes. Cooling followed.

It is interesting to see how close the cooling water exit temperature approached the batch temperature. These first-year students had not had a course in heat transfer at this stage, so they did not recognize how efficient the cooling coil inside the vessel performed. They did note that the plots of temperature acquired automatically were smoother compared to temperatures acquired manually. Figure 7 shows a set of data collected manually as read from thermometers by students. The "noise" observed in this particular figure is comparably low for manually acquired data typically collected by students.

Students also made observations about automatic-versus-manual control. One student noted that when the plant is operated under automatic control, operators are free to do other vital jobs. He also noted that running the rig remotely (over the Internet!) would maintain a safe distance for dangerous reactions.

The students were also required to do energy balances around the reactor for both the heating and cooling operations. For the heating cycle, students typically reported a heating efficiency of about 45% (calculated as [Heat absorbed by water]/[Heat released by condensing steam]). Two explanations exist. One, that the apparent steam condensate collected is large because it included hold-up from previously condensed steam; the second explanation, which most students mentioned, was that the stainless reactor itself had thermal capacity and also required heating. Heat losses also exists, but are relatively small in comparison.

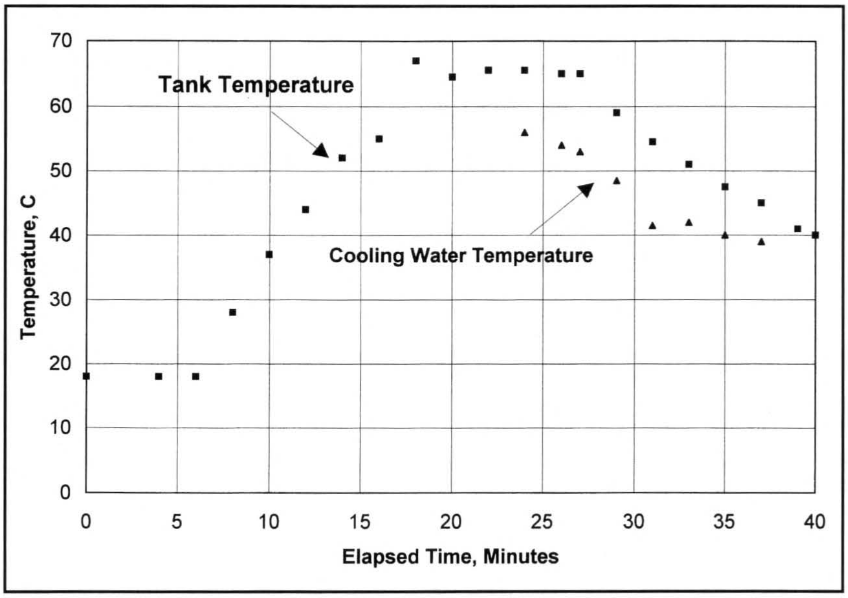

Figure 7. *Temperatures as a function of elapsed time as recorded by a student group during the manual run.*

What did we discover during the first few runs? We missed telling the students to record the inlet cooling water temperature; this has now been included in the procedures. Hindsight is 20/20.

CONCLUSIONS

The experiment provides a worthwhile educational experience for relatively inexperienced students. In particular, the advantages of automated operation are demonstrated. Further, students are able to practice their IT skills and to apply basic energy-balance techniques.

ACKNOWLEDGMENT

The authors acknowledge Thomas Holgate and Tracy Wong, first-year students at the University of Nottingham, whose data were used as examples in this paper. The authors also acknowledge the assistance of Fred Anderton in wiring the circuits required to set up the automation of the sequential control unit. Prof. Willey acknowledges Northeastern University for permission to do a sabbatical at the University of Nottingham during the fall of 1997.

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THE EFFECTIVE USE OF LOGBOOKS IN UNDERGRADUATE CLASSES

JENNIFER I. BRAND
University of Nebraska • Lincoln, NE 68588-0126

Substantial writing assignments are required in an increasing number of undergraduate technical courses. They are usually intended to give the students practice in formal written communication, which will probably be an important part of the jobs most of them will choose after graduation.

With these jobs in mind, the assignments tend to concentrate on teaching the students to write formal reports and polished memos, two common forms of professional writing. Not all of the important professional writing that students will do in future jobs will be in these commonly emphasized formats.

This article discusses a semester-long writing assignment, the class-related logbook, that concentrates on teaching the process of using regular writing as a powerful professional tool apart from the formal documents required on the job. The assignment itself will be discussed in the format it has taken after three successful years of implementation in the first junior-level transport class for chemical engineering majors where class sizes ranged from fourteen to thirty-three students.

The need for this innovative logbook assignment evolved partly from the changing undergraduate engineering curriculum. Engineering students once took more hours of undergraduate laboratory courses and were required to keep lab notebooks. These notebooks were graded according to rigid rules concerning completeness, organization, and clarity. Currently, the trend in many schools is away from these laboratory courses, for a variety of reasons including expense, safety, intensity of instructional resources, and logistics of fitting all the current requirements into shrinking credit-hour limits.

While some parts of the laboratory experience can be replaced by computer simulations, writing as a tool of organization, planning, and discovery that was inherent in good laboratory notebooks seems to have fallen from the curriculum. The class-related logbook revives this use of writing as a technical tool.

There are also sound pedagogical reasons for including writing assignments in addition to the typical formal reports and memos. Writing can be a powerful tool for information processing: for assimilation, for organization, for clarification, for analysis, and for synthesis. In short, all levels of higher-order cognitive learning (as outlined in Bloom's Taxonomy,[1] for example), can be more efficiently achieved with good personal writing skills as tools.

Since we want our students to be lifelong learners, this habit of using writing as a problem-solving tool should be taught and practiced in conjunction with their classroom experiences, just as their other intellectual tools such as calculus, computer literacy, and the ability to produce formal documents are.

The idea of class-related logbooks sounds like a simple and laudable way to develop valuable personal writing habits early in the undergraduate career, but there are certain pitfalls to successful implementation of the practice. This article includes ways of avoiding three of the most common pitfalls: unrealistic professorial expectations, inadequate assignment design and presentation, and ineffectual grading practices.

Jennifer I. Brand *is Assistant Professor in the ChE Department at the University of Nebraska-Lincoln. She received her PhD in chemical engineering at the University of California, San Diego. and her BSE and MSE from the University of Michigan. She has worked as a chemical engineer in private industry and at Oak Ridge National Laboratory. She has taught graduate and undergraduate courses in thermodynamics, transport processes, biotechnology, air pollution, and semiconductor processing.*

THE ASSIGNMENT

The class-related logbook assignment consists of three required sections: a journal, chapter outlines, and reference pages. (Students have the option of adding other sections for their own use, but seldom do.) Each section has an individual function and format. When combined, the whole logbook is an integrated study tool demonstrating the interrelationship among different components. The logbook is graded and makes up a little under ten percent of the student's grade, enough to insure that they do the assignment but not enough that they overemphasize it to the detriment of their other learning tasks.

. . . writing as a tool of organization, planning, and discovery that was inherent in good laboratory notebooks seems to have fallen from the curriculum. The class-related logbook revives this use of writing as a technical tool. . . .
This article discusses a semester-long writing assignment, the class-related logbook, that concentrates on teaching the process of using regular writing as a powerful professional tool apart from the formal documents required on the job.

Table 1 (next page) shows an actual class handout given to the students explaining the assignment. This written definition of the logbook assignment includes general guidelines for informal professional writing, instructions for each of the sections, and examples of acceptable journal entries. Students are advised in writing, via this document, that while the logbook is theirs, it will be a "semipublic document," and parts of it may be shared in a professional manner with the class as a whole or with other academicians. They are verbally assured that this public sharing will not include the explicit identification of individuals without their consent and any requests for confidentiality will be honored.

The purpose of the journal is threefold: to encourage habitual writing as an organizational tool, to teach the use of chronological records as measurements of progress and as indicators of patterns, and to give students a regular opportunity to communicate with the instructor concerning the course and their progress. Anything relevant to the class can be included: their insights, their questions on procedure or content, their personal methods or circumstances that legitimately influence their class performance or their learning experiences. Honesty is required (although they are not required to bare their souls). Special assignments are required throughout the semester to help structure the journal, as will be discussed below. Instructor feedback on the journal is the key to success in developing the good writing and communication habits the journal is designed to foster.

The purpose of the chapter outlines is to demonstrate to the students the strengths of this traditional and effective study tool—one that seems to be falling by the wayside in popularity without being replaced by anything that has been demonstrated to be as effective and as simple. Students who stay current on their chapter outlines will read the assignments in a timely manner and will usually read more thoroughly. Instructor feedback on these outlines is a valuable tool in helping them hone their abilities to prioritize and to understand how others have organized material. The outlines themselves are useful tools for studying for tests and for taking open-book tests.

The reference pages are the students' own organizational products, tailored to their individual needs. These pages contain the highlights of the key concepts presented in the course, as well as any useful information from other courses. A typical set of reference pages might include a page of important dimensionless numbers, with defining equations as well as a few words about the physical meaning and applications, a page or two of named equations and key definitions, and a page of "reminders" with a few facts from a math course or useful variables such as the viscosity of air and water at standard conditions. There may also be a brief annotated bibliography or a list of particularly useful reference sources.

Unlike the journals, which are chronological, and the outlines, which are dictated by someone else's organizational style, the reference pages are an opportunity for the students to learn how they can most effectively organize material for themselves. Supplemental material (usually from previous classes) is often included in the best examples of these pages. They are also useful tools for studying and taking tests. The reference pages are usually quite compact, and therefore the students will find them to be the most useful summary of the course. They are often used to review key concepts when students take subsequent courses or when they study for comprehensive exams, such as professional licensing exams.

COMMON PITFALLS: HOW TO AVOID THEM

Pitfall I: Unrealistic Professorial Expectations

One of my colleagues tried using my logbook assignment and gave up a few weeks into the semester. He found that the good students will keep good logbooks, but similarly, the students who didn't do the other assignments kept bad logbooks if they kept them at all. He concluded that the logbooks weren't serving his purpose of making the

TABLE 1: CLASS HANDOUT FOR LOGBOOKS

What? You will be required to keep a logbook for this class. The logbook will be yours, so you have some freedom in what you put in it and how. It is, however, a "semipublic document," so there are some requirements and guidelines. I will read it on a regular basis and we may share parts of it formally in class. I may make copies of part or all of some of the logbooks for use in the future.

Why? The purpose of this logbook is communication. It is an ongoing written progress report of your work. It will let me know how the class is progressing; it will let you see your progress and may help you in seeing patterns to accelerate or ease that progress. Logbooks are also powerful tools in the real world (see Clifford Stoll's *The Cuckoo's Egg,* a true thriller where a physicist cracks an international computer spy ring and convicts the spies because his logbooks are used as documentation in court).

How? A three-ring binder with dividers?

Guidelines and Requirements

- It must be legible and understandable.
- The writing should be professional but not necessarily polished. Be clear, concise, specific, and accurate. Be natural, but not too relaxed. (Do not use language you would not use in front of a significant other's parents the first time you meet them, for example.) Grammar need not be perfect (Contractions and sentence fragments are okay.) Active voice is preferred.
- It should be scrupulously honest. (Recall that honest does not necessarily mean exhaustive. Everything you say should be true, but you needn't say everything.) You are not being graded on how easily or independently you pick up material outside of class or whether or not you like the subject or class.
- Every entry should be dated
- The logbook will have at least three sections: the journal, the chapter outlines, and the reference pages.

The Journal • This is the most free-form section. There will be some specific questions and topics assigned for discussion, and these must be addressed in a professional manner in the journal, within the time frames specified. They should also be clearly marked. In addition to these assignments, anything that relates to this class belongs in this section. It should not contain irrelevant thoughts, but tangential thoughts are okay. How you study for the class, what works well, what doesn't, why and how it works (or doesn't) can go in; with whom you study is okay; why you couldn't study (not excuses, but reasons); what was good or bad or frustrating or boring or interesting or hard or easy about the day's class or homework problems or reading assignment (The more specific details, the more useful such entries will be for both you and me.); a supplementary source you found particularly useful; a connection with something in another class or some personal experience; a worked-out example or scratched notes on problem approaches might be included. You will find it useful to summarize periodically. An example of a journal is attached.

Chapter Outlines • This is your personal annotated index of the important parts of the textbook. Construct it in a way that is useful to you. You may want to emphasize points that were difficult for you, de-emphasizing the "intuitively obvious" subjects, even if those subjects are treated extensively in the book. Cross-reference ideas and equations to pages in the text. You may also want to cross-reference pages in your notes or other materials. A page or two should be enough to hit the important ideas in each chapter. Keep in mind that properly constructed outlines can be very useful study guides and invaluable for taking open-book tests.

Reference Pages • This section will contain things like a bibliography, the list of named equations, key concepts, charts, etc. Organize this section in a way that is logical to you, not just by chronological order in book or course notes. This section, too, can be invaluable for taking open-book tests.

A Sample Journal (Based on Student Journals in a Fluid Mechanics Class)

9/15—worked this afternoon with Scott C. and Jason B. for two hours on problem 3-15. Brick wall! After dinner, reviewed lecture notes for 9/9 while waiting for the laundry. THIS IS THE SAME PROBLEM EXCEPT IN SPHERICAL COORDINATES!

9/16—No clue what that lecture meant! When can you assume what for boundary conditions? It seems so arbitrary. How do you know where to put the origins? And, of course I could have answered any other class question today, except the one she asked me! How does she always pick the part of the reading I didn't get to to ask me?

> ASSIGNED DISCUSSION "Write directions for designing and making an Egyptian water clock. The explanations of what you are doing and why should be clear, accurate, and concise, and easily understood by a bright 12th grade science class. Sketches and equations may be useful." [...Two pages of discussion omitted from logbook example...]

9/17—No way am I going to torture myself with that stupid stuff on a Friday night!

9/20—I just know there will be a quiz tomorrow. Always is when we have big assignments due in thermo. Will it be vocabulary or math? I only have time to study one! Scott and Jason came over and we worked for about four hours on 3-11. Another hour just getting the details on 3-15. Too much work! And where are the physical properties at that temperature? I just want to stop pollution, not write differential equations. So I'll review vocabulary lists from Chapter 1-3 (in my reference pages).

9/21—I guessed right. Vocabulary quiz. I think I did okay. At least I finally have the difference between continuity and continuum down. Karyn said she and Skylar only needed three hours for the whole homework set. They used White's book (on reserve in the library) because it has a good summary of when to apply boundary conditions and the viscosities and densities are in Perry's! Wish I'd known. Jim asked how to know when to use which boundary conditions. "Experience" was the answer—so what do we do, take the class five times? Still, when we broke into small groups to do b.c.'s for the examples, I got most of them right by the end of group time. Small group work seems like an effective way to "experience" stuff like this.

9/22—So if there is a no-slip condition at a wall, and you can get non-symmetric velocity profiles with plates moving at different conditions, is this why you get those divots in the cake mix next to the beaters? And, come to think of it, why does the cake batter always want to climb up the beaters? And why don't all the bubbles coalesce during baking? (Baked a cake for Chris's birthday tonight.)

> ASSIGNED DISCUSSION "Record all valves you use for a twenty-four hour period. Include a description of the valves, what they were used for, what flow rates, what kind of valves they were, what conditions of service they see, what they are made of, special design features, or anything else relevant. Evaluate the selection of the particular valves for the particular applications. Give preferred alternatives, if any." [...Valve list and discussion omitted from logbook example...]

students come to class prepared for lecture. This is not an unexpected result.

A class-related logbook is not a panacea for student learning or attitude. Its purpose is to help the student develop learning tools not specifically emphasized in other parts of the curriculum. For instance, assigning chapter outlines will not make the incorrigible student read the chapter, nor will it be the only reason the good student does a reading assignment. The main virtue of the outline assignment is that it shows the student a proven way of organizing challenging new material as a step to learning it. Whether or not this particular material challenges this particular student is irrelevant. When the student eventually does encounter challenging material, he should have various tools, such as outlining, in place so that the new content, not the concurrent development of the learning tools to master the material, will be the student's task at hand. The reasonable expectation here was not that all students would come to class prepared because logbooks were assigned, but that students who kept logbooks would improve their learning skills.

Another reasonable expectation for the instructor is that communication within the class will be greatly improved, especially if the instructor grades the journals encouragingly, as discussed below. The positive benefits of good student-instructor communication hardly need extolling here. The instructor will have great quantities of class-related information from the students for a surprisingly low investment of his time. In addition, that time can be scheduled at his convenience.

Pitfall II: Inadequate Presentation of the Assignment

To the students, the idea of "free-form" writing in a technical class sounds vague, confusing, and since it is a graded assignment, more than a little frightening. The instructor has three powerful tools to overcome student's discomfort: explanation, examples (modeling), and specific, focused mini-assignments. The handout in Table 1 demonstrates the use of each.

Collecting and commenting on the assignment frequently at the beginning of the term, as well as continued modeling throughout the first weeks of class, is a valuable use of time. As the students become more comfortable with the assignment, their anxiety will subside and the logbook will take very little class time the rest of the semester. The modeling in the initial part of the class usually is most successful if it draws on good examples from other students' logbooks, as well as from class projects (it takes about ten minutes to demonstrate how to outline a chapter from scratch). The mini-assignments are usually designed to integrate previously covered material and real-life experiences or to summarize and integrate recently studied material.

After a few summarization assignments, students often begin summarizing periodically on their own, an indication that their writing tools are developing and becoming a habit. A particularly useful integrative summary is asking the students to predict what will be on an upcoming exam. Another is to ask them to design a flowchart for problem solving, based on their own problem-solving processes. Comparing their flowcharts from the beginning and the end of the term can be most instructive for both the students and the instructor.

Pitfall III: Grading and Instructor Feedback

Grading must reflect the process, not the product, especially early in the semester and in grading the journals. Some specific grading guidelines for the three parts of the logbook follow. In general, students should be allowed the freedom to make mistakes and should not be penalized for originality. Having said that, leaving mistakes uncorrected or not revisiting erroneous logic by the next time the logbook is reviewed is a legitimate reason for lowering grades. Some of the more specific detailed assignments may entail special grading criteria such as completeness and accuracy, which are mentioned at the time of the assignment.

Logbooks are graded on a ten-point scale each time they are collected, which is twice during the first three weeks of the term and then irregularly at two-to-four-week intervals thereafter. The journals are worth six to eight of the ten points. Chapter outlines and the reference pages are worth two points each early in the term, later decreasing to one point each.

Since chapter outlines and reference pages are good tools for studying and test taking, the students usually need little grade incentive to do well on those sections after the first test. The journals are more heavily rewarded by grades to encourage the students to develop the habit of making the intellectual efforts required to produce good journal entries.

The journal should be graded encouragingly, especially early in the semester. This assignment is strange to students, who are usually more accustomed to worrying about "what the professor wants" rather than how to acquire the lifelong learning skills the journal promotes. Since this journal is to encourage the habit of informal professional writing, it should be rewarding, not intimidating.

The actual value of the early grades for journals should be based on whether specific assignments are carried out and whether a good faith effort is being made to keep a journal according to the guidelines. As the semester progresses, expectations for the journal entries will be raised. Later in the term, grades may reward reasonable attempts for seeking answers, not just wondering about things. By the end of the term, the students should be able to attempt answering, at an appropriate level, most questions that they pose for themselves. These attempted answers should be reasonable, logical, and accurate, at a level appropriate to the students'

Continued on page 231.

TWO SIMPLE EXPERIMENTS

For The Fluid-Mechanics and Heat-Transfer Laboratory Class

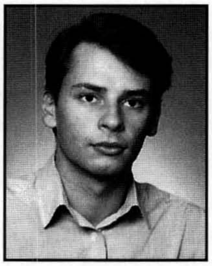
Manuel A. Alves, Alexandra M.F.R. Pinto, João R.F. Guedes de Carvalho
Universidade do Porto • Rua dos Bragas • 4050-123 Porto, Portugal

Fluid mechanics and heat transfer are important subjects in undergraduate courses in chemical engineering, and surely there is no danger of overemphasizing the importance of performing simple illustrative experiments that the students can fully comprehend. A wealth of demonstrative experiments are available commercially in kits, but they tend to be expensive and leave the user in some form of dependence on special spare parts in case of breakage.

The experiments described in this paper are cheap to build and rely on materials and instruments readily available in most engineering departments. The equipment needed is

- An electrical oven
- A digital millivoltmeter
- Two thermocouples
- A fan
- A viscometer
- Two ball valves
- Plastic beakers
- An anemometer

and some pieces of metal and nylon rods and acrylic tubing that can be machined in half a day in a rudimentary workshop.



***Manuel A. Alves** graduated in chemical engineering from the University of Oporto in 1995 and immediately began teaching as a Demonstrator in the Chemical Engineering Department there. He became a Teaching Assistant in 1996. His research interests are in fluid dynamics and applied thermodynamics.*

***Alexandra M.F.R. Pinto** graduated in chemical engineering from the University of Oporto in 1983, received her PhD from the same university in 1991, and is now an Assistant Professor. She has taught courses in heat and mass transfer and ChE Laboratories, and her research interests are in fluidized bed combustion and in the hydrodynamics of multiphase flows.*

***João R.F. Guedes de Carvalho** graduated in chemical engineering from the University of Oporto in 1971 and received his PhD from the University of Cambridge in 1976. He is Professor of Chemical Engineering at the University of Oporto, and his research interest are in multiphase flow and associated problems of mass and heat transfer.*

EXPERIMENT 1
Laminar Film Flow Around Long Cylindrical Bubbles

Most students will be familiar with, or will easily understand, a wetted-wall column, but from our experience, few will have come across the concept of cylindrical bubbles. Yet, these are easily formed during continuous bubbling in narrow bubble columns if the gas flowrate is increased sufficiently, and also in vertical boiler tubes if the heating rate is high.

An easy introduction to cylindrical bubbles is afforded by means of a simple experiment in which a long and narrow acrylic tube is initially filled with water to within a few centimeters of the top. A stopper is then used to close the tube, before turning it upside down. A cylindrical bubble will be seen rising up the tube (see Figure 1a), and its velocity, U, is easily determined by timing the rise along a given height. If the experiment was repeated with tubes of different diameters, D, it would be seen that

$$U = 0.345(gD)^{1/2} \tag{1}$$

where g is the acceleration due to gravity. (The same type of experiment can be performed to show that U is independent of bubble length.)

Equation 1 is valid for cylindrical bubbles in liquids of low-to-moderate viscosity, which according to Wallis[1] corresponds to the criterion

$$N_f = \left(gD^3\right)^{1/2} / \nu > 300$$

where N_f is the dimensionless inverse viscosity and   is the kinematic viscosity of the liquid.

The experiment we propose may be seen as a variation of the one described above. If a cylindrical tube is completely filled with liquid and a stopper is used to close it at the top, and if the stopper at the bottom of the tube is removed, a growing gas slug will be seen rising up the tube core while liquid will continuously discharge at the bottom along the wall (see Figure 1b).

The volumetric balance of gas and liquid flowing through any cross section of the tube requires that

$$Q = \frac{\pi}{4}(D - 2\delta)^2 U \tag{2}$$

where Q is the volumetric flowrate of liquid running down along the tube wall, and δ is the thickness of the liquid film. If $\delta / D << 1$, the curvature of the liquid film can be neglected and Nusselt's analysis for film flow is known to give[1]

$$q = \frac{g\delta^3}{3\nu} \tag{3}$$

where $q = Q / \pi D$ is the liquid flowrate per unit wetted perimeter. This equation is deduced for laminar flow, which is normally observed when

$$Re_f = \frac{4q}{\nu} = \frac{U(D - 2\delta)^2}{\nu D} < 1500 \tag{4}$$

where Re_f is the film Reynolds number.

Substitution of Eq. (3) into Eq. (2) leads to

$$U = \frac{4gD}{3\nu} \frac{\delta^3}{(D - 2\delta)^2} \tag{5}$$

and with U from Eq. (1), we get

$$\frac{\delta^3}{(D - 2\delta)^2} = \frac{\nu}{3.86(gD)^{1/2}} \tag{6}$$

It should be remembered that this equation is valid only if $N_f > 300$ and $Re_f < 1500$. For given values of D and g, Eq. (6) is shown to relate δ with ν.

In film flow, a more general relationship between the dimensionless film thickness, ξ, and the film Reynolds number is obtained if the definition of Re_f is substituted in Eq. 3,

$$\xi = \frac{\delta}{D} N_f^{2/3} = 0.909\ Re_f^{1/3} \tag{7}$$

(valid only for laminar flow) as pointed out by Wallis.[1]

Experimental Work

A 1.5-m length of 19-mm i.d. acrylic tube is adapted to one side of a 3/4" ball valve, the other side of which is fitted to one end of a 1-m length of the same tube, and fitted with another ball valve at the other end. The resulting column is aligned vertically above a plastic bucket, as shown in Figure 2, and a stopper is placed at the bottom before filling the column completely with liquid (a detailed drawing of a nylon adapter used to connect the tube with the valves is shown in Figure 2).

The valve at the top is then closed and the stopper at the bottom is removed to let a growing gas slug form and rise up the tube. The slug will be allowed to rise freely until its nose is some 0.3 to 0.4 m above the ball valve, at which time the valve will be suddenly closed and a plastic beaker placed (simultaneously) right under the column. The liquid collected in the beaker will then be that making up the film running down the tube wall over the length H, measured

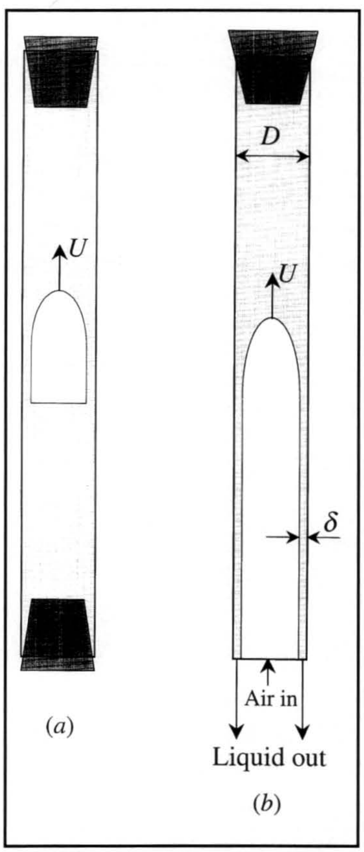


Figure 1. *(a) Slug rising in a closed vertical tube; (b) film flow around a growing slug.*

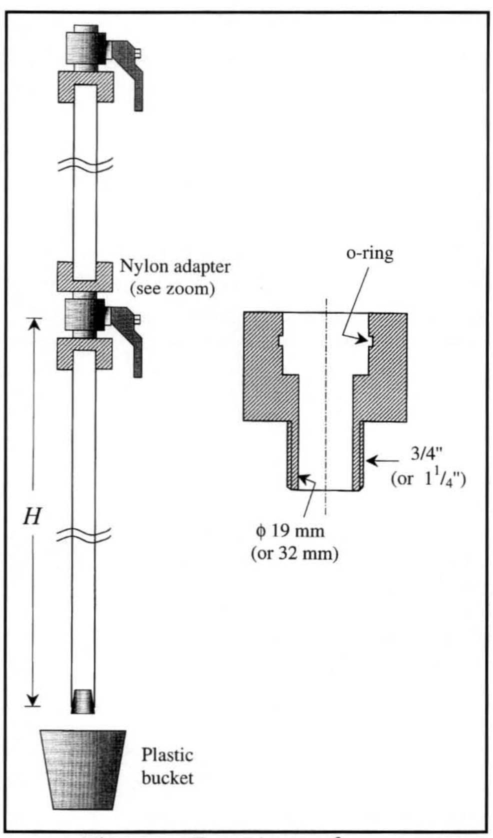


Figure 2. *Experimental setup.*

between the bottom of the column and the ball valve. The thickness, δ, f the liquid film is determined from the volume of liquid collected, V, through

$$V = \frac{\pi}{4} H\left[D^2 - (D - 2\delta)^2\right] \tag{8}$$

It is a simple matter to repeat the experiment with liquids covering a range of viscosities (we used glycerol solutions with viscosities up to 15×10^{-3} kg/ms). A 32-mm i.d. column can also be used, with 1 1/4" ball valves (note that the internal diameter of the ball valve must be exactly the same as that of the column). Measurement of slug velocity is also simple through timing of the passage of its "nose" between two marks about 1m apart.

Results and Discussion

Results obtained by our students are plotted in Figures 3 and 4, and the agreement between theory and experiment can be seen to be excellent (average deviation in δ less than 50 μm, or about 5%).

Although the experimental technique is rather crude, our experimental points fall closer to the theory than those reported in Figure 11.8 of Wallis.[1]

Pedagogical Comments

The study of laminar flows is an important part of a fluid mechanics course. The two most common experimental illustrations are laminar flow in a tube (Poiseuille's formula) and free settling of a sphere in a viscous liquid (Stoke's law). Film flows are an important class of laminar flows (*e.g.,* in lubrication, wetted-wall columns, and filmwise condensation), but they are not normally illustrated experimentally. This experiment provides a vivid illustration of the theory of laminar film flow and, as an additional bonus, it combines it with a very simple analysis of two-phase flow

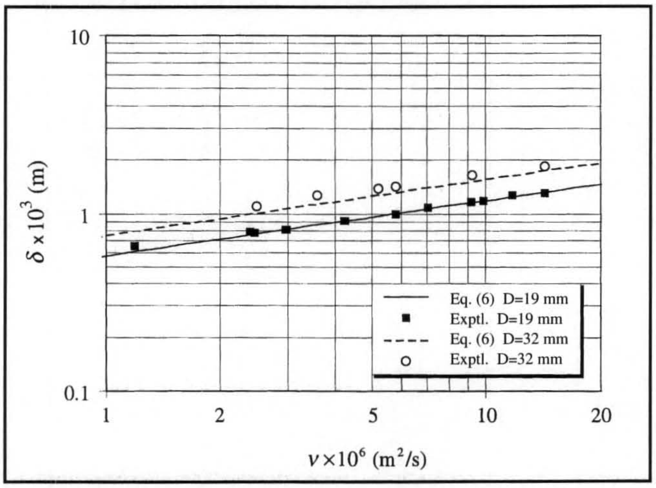


Figure 3. *Film thickness as a function of the kinematic viscosity for D=19mm and D=32mm. Comparison between Eq. (6) and experimental results obtained by students.*

The actual demonstration is deceptively simple for the students. They only have to remove a cork and a few seconds later close a valve while simultaneously placing a beaker under the column. But from our experience, the interpretation of the results—namely, the interplay between upwards gas flow and downwards liquid flow, (with volume conservation (!))—is very instructive. Invariably the students are amazed when they find the close agreement between experimental and theoretical values of δ.

EXPERIMENT 2
Heat Transfer in Free and Forced Convection Around Cylinders

A metal rod (typically 0.15m to 0.25m long and 15mm to 30mm in diameter) is initially heated in an oven to around 90°C, and then suspended from two thin wires with its axis horizontal, as shown in Figure 5. A thin sheathed thermocouple is then introduced into a hole with a diameter only slightly larger than the thermocouple and drilled near the axis of the rod. This thermocouple is connected to a reference thermocouple immersed in an ice-water mixture and to a mV meter, from which values of e.m.f. are read at regular time intervals (of between 30s and 90s, depending on the cooling rate of the rod). More "advanced" options are the use of thermocouple compensation and direct data logging on a computer.

In the natural convection experiment, the rod is allowed to cool in still air, whereas in the forced convection experiment an electrical fan is used to blow the air in a direction perpendicular to the axis of the rod. An anemometer is then needed to measure the velocity of the air near the rod.

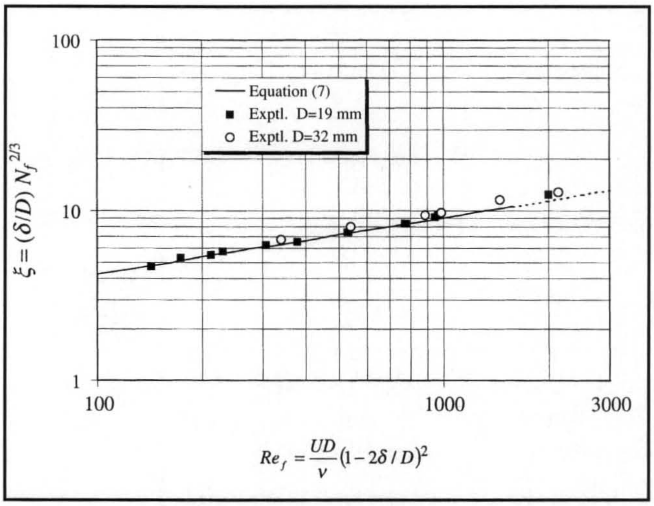


Figure 4. *Effect of Reynolds number on dimensionless film thickness. Comparison betwen experimental points obtained by students and Eq. (7).*

Data Treatment

If a heat transfer coefficient, h, is defined, the cooling law for the rod is

$$-mC_p \frac{dT}{dt} = hA(T - T_0) \qquad (9)$$

where m is the mass of the rod, with external area A and specific heat capacity C_p. The temperature of the rod at time t is T, and T_0 is the temperature of the air far from the rod, taken to be invariable in time. If the variable $\theta = T - T_0$ is defined, integration of Eq. (9) from t=0, for which time $\theta = \theta_i (= T_i - T_0)$, leads to

$$\ell n\, \theta = \ell n\, \theta_i - \left(hA / mC_p\right)t \qquad (10)$$

where hA/mC_p has been taken to be constant over the time interval considered. Equation (10) suggests a representation of the experimental data as $\theta = \theta_i$ vs t in a semilog plot, and in Figure 6 the data obtained in our lab with a Dural rod (L=0.250m, d=0.0250m) cooling in still air are reproduced.

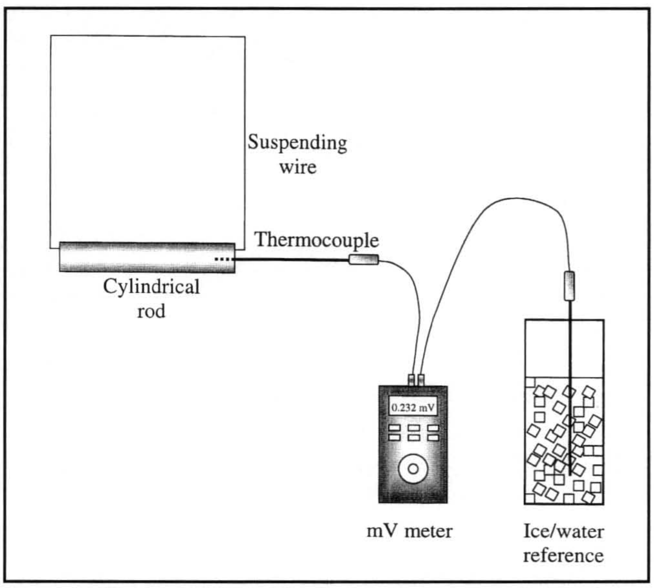


Figure 5. *Diagram of experimental setup.*

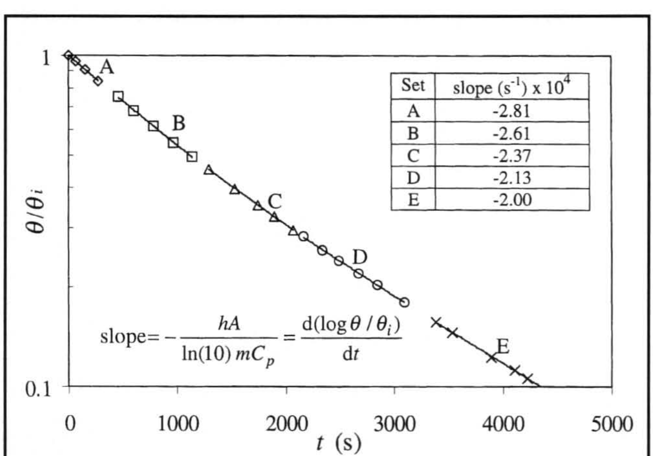


Figure 6. *Cooling curve for natural convection (dural rod, d=0.0250m, L=0.250m).*

Natural Convection

It is important in this part of the experiment to use well-polished rods that are not covered by a thin oxide layer, so that the contribution of radiative transfer becomes negligible. A careful look at Figure 6 shows a slight upward curvature in the alignment of the experimental points; this is because h decreases with the temperature of the rod, for natural convection. If the data in Figure 6 are sliced into a number of successive time intervals, with each containing a number of experimental points, it is possible to determine the best-fit straight line for each time interval, and from the corresponding slope the value of h is found.

The values of h obtained in this way are represented in Figure 7, and they are seen to compare extremely well with the correlation given by Holman,[2] which for atmospheric air at moderate temperatures reduces to

$$h = 1.32\,(\theta / d)^{1/4} \qquad (11)$$

with h in W/m^2K, θ in K, and d (the diameter of the rod) in meters.

Forced Convection

For the conditions in our experiments, the heat transfer coefficient for cooling under forced convection has a negligible dependence on the temperature of the rod and as a result log θ / θ_i vs. t plots as a straight line for each value of air velocity.

In order to compare the values of h obtained from these lines with predictions from Fand's correlation[2]

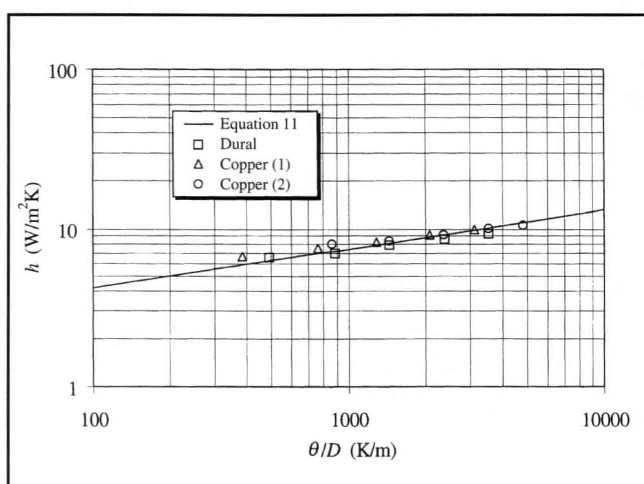


Figure 7. *Heat transfer coefficients in natural convection.*

$$Nu = \left(0.35 + 0.56\ Re^{0.52}\right) Pr^{0.3} \tag{12}$$

it is necessary to measure the velocity with which the air approaches the cylinder, u_∞. In Eq. (12), $Nu = hd / k$ is the Nusselt number, $Re = \rho u_\infty d / \mu$ the Reynolds number, and $Pr = C_p \mu / k$ Prandtl's number. All the physical properties are for air at mean film temperature $\left(= \left(T + T_0\right)/2\right)$. In our experiments, where transient cooling is observed, values of Nu, Re, and Pr could be evaluated at different times (in each experiment we evaluated these dimensionless groups near the beginning and near the end of the cooling period, to obtain two points on the plot in Figure 8).

Results and Discussion

Our students performed experiments with three different metal rods (see Table 1), and the data obtained were used to organize the plots in Figures 7 and 8. It can be seen that the experimental points fall quite close to the correlations suggested in the literature, even though the experimental technique is rather crude.

Pedagogical Comments

Students like this work for a variety of reasons. (1) They have an opportunity to successfully test the theory of transient heat transfer for lumped parameter systems. (2) They obtain individual values of the heat transfer coefficient, which (some are surprised to see) compare well with those given by available correlations. (3) If two rods of the same size are used, one made of duralumin and the other made of copper, the latter cools more slowly under otherwise similar conditions, due to its higher heat capacity. For the weaker students, it is intriguing to see that the same heat transfer coefficients are obtained for both rods. (4) The effect of temperature difference on the heat transfer in natural convection is also brought out vividly. (5) The importance of radiative heat transfer is brought to evidence if two equal rods are used in the natural convection experiment, of which one has been allowed to oxidize so as to lose its shiny appearance.

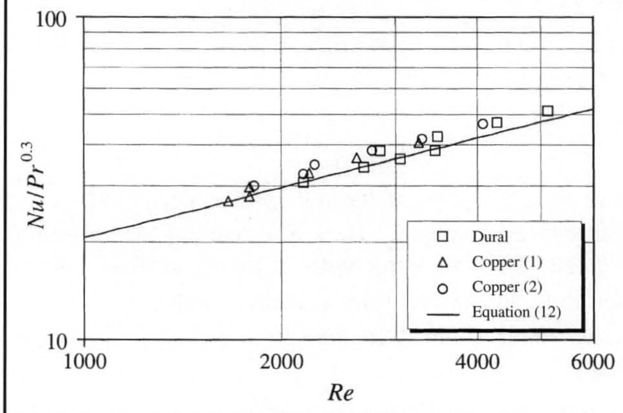


Figure 8. *Dimensionless heat transfer coefficients in forced convection.*

TABLE 1
Characteristics and Properties of the Metal Rods Used in the Experiments

	d(m)	L(m)	m(kg)	$C_p^{(*)}$(J/kg.K)
Copper (1)	0.0158	0.250	0.440	383.1
Copper (2)	0.0199	0.250	0.693	383.1
Duralumin	0.0250	0.250	0.334	883.0

(*) Ref. 2.

NOMENCLATURE

- A area for convection (m^2)
- C_p specific heat capacity (J/kgK)
- D column internal diameter (m)
- d diameter of rod (m)
- g acceleration of gravity (m/s^2)
- H length between bottom of column and ball valve (m)
- h heat transfer coefficient (W/m^2K)
- k thermal conductivity (W/mK)
- L length of rod (m)
- m mass of rod (kg)
- N_f dimensionless inverse viscosity (-)
- Nu Nusselt number evaluated at mean film temperature (-)
- Pr Prandtl number evaluated at mean film temperature (-)
- Q volumetric flowrate of the liquid (m^3/s)
- q liquid flowrate per unit wetted perimeter (m^2/s)
- Re Reynolds number evaluated at mean film temperature (-)
- Re_f film Reynolds number (-)
- t time (s)
- T temperature of rod (K)
- T_0 ambient temperature (K)
- U velocity of cylindrical gas bubble (m/s)
- u_0 air velocity (m/s)
- V collected volume (m^3)
- δ film thickness (m)
- μ dynamic viscosity (kg/ms)
- ν kinematic viscosity of the liquid (m^2/s)
- θ temperature difference, $T-T_0$ (K)
- θ_i value of θ at t=0 (K)
- ρ density (kg/m^3)
- ξ dimensionless film thickness (-)

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2. Holman, J.P., *Heat Transfer,* 8th ed., McGraw-Hill International Edition, Chap 6-7 (1997) ❒

EFFECTIVE USE OF LOGBOOKS

Continued from page 225.

educational achievements. For example, specific assignments, such as summaries, can be graded more objectively and rigorously, for completeness and accuracy.

Instructor comments, rather than grades, are the real key to making the journal a valuable learning tool for enriching professional writing and organizational skills. Comments that praise curiosity, originality, insight, and innovative organization will increase students' efforts in journal writing. Comments that demonstrate the instructor's desire for open communication will make the journals more useful for the instructors. Also, instructors should address specific concerns raised in the journals, referring students to the text or other references rather than just answering questions. In this way, students will rely on their own initiative, rather than the instructor, in seeking answers to questions that have solutions within their capability to discover.

Copious instructor comments might seem to imply a huge investment in time, but experience has shown the opposite. Logbooks can be rapidly read. I often collect and read twenty journals (but not the reference pages or outlines) while proctoring fifty-minute class exams. The chapter outlines and reference pages generally need little correction after the first week or two of class, because the writing assignments are so concrete that engineering students have little trouble with them. (For a large class, these two sections might even be assigned to a teaching assistant for grading.) If term projects are required, the time spent on grading logbooks also pays a time dividend at the end of the term. Students produce better, more organized, and more easily graded projects when they have journal feedback throughout the semester on their writing and on their developing projects.

One technique that is useful in minimizing instructor effort while insuring copious useful instructor feedback is to write group remarks for common questions, problems, or insights. Instead of the instructor writing "Does this REALLY apply in the transition region?" in ten or twenty journals, he or she can distribute these written general remarks in class and the students can incorporate them into the individual journals. In addition to saving time, this method also helps the students realize they were not the only ones who had this particular insight or concern or error. This sort of realization bolsters student confidence in the rewards of journal writing and increases their enthusiasm. Journal entry quality seems to be directly correlated with confidence and enthusiasm.

The chapter outlines are the most objectively graded section. Format is generally up to the student, but it is evaluated for usefulness as a study tool. For example, the outlines must have proper page number annotation to serve as open-book tools. The outlines should be a page or two long, highlighting and referencing the key concepts of the chapter. Long passages copied from the text receive lower grades, as they do not demonstrate the same ability to distinguish the main from the supporting, incidental, or supplemental ideas and facts. Content is graded rigorously on completeness and accuracy.

It is usually obvious from the content whether or not the students are really doing the intellectual work of reading and outlining, rather than just copying the table of contents or chapter headings. Such superficial efforts should not be rewarded with good grades. Again, modeling the concepts, by either composing the outline of the first chapter in class or by handing out examples of good student outlines early in the term will let the students know what is expected of them and improve their ability in outlining.

The reference pages are the student's personal study guides and need little grading. Instructor remarks can be limited to suggestions on possible omissions. Grades are generally quite liberal, but two behaviors should result in lowered grades for this section. The first is inaccuracies and errors that are pointed out by the instructor and are left uncorrected. The second is incorrect or inadequate referencing of sources, again, if left uncorrected.

SUMMARY AND CONCLUSIONS

For the past few years, I have had positive experiences integrating writing and communication into undergraduate chemical engineering classes by means of logbooks, which include journals, chapter outlines, and reference pages. Although journals are a well-established pedagogical tool in many arenas, from music composition classes to English classes to teaching-methods workshops, there are definite challenges in using the device well in a technical course.

With proper structuring, the logbooks have been a positive communication and organizational tool for the students. They report that they like keeping the logbooks and find them useful as well. They feel that their opinions and concerns are being heard and they especially enjoy the tangible feeling of progress that looking over the journal and the summary assignments gives them. They learn and practice valuable writing skills not usually required and graded in the classroom.

The instructor also benefits from the logbooks, which provide an effective, convenient, and efficient manner of communicating with the students and monitoring and enhancing their learning experiences.

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EXPERIMENTS ON VISCOSITY OF AQUEOUS GLYCEROL SOLUTIONS

Using a Tank-Tube Viscometer

KYUNG KWON, SAMMAIAH PALLERLA, SANJEEV ROY
Tuskegee University • Tuskegee, AL 36088

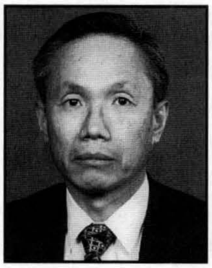
At Tuskegee University we have added a new laboratory experiment for the fluid mechanics and transport phenomena laboratory (the Unit Operations I Laboratory) that investigates the effects of both water concentration and temperature on the viscosity of aqueous glycerol solutions. The experiment is designed as an extension of the fluid mechanics course (offered to sophomore students), the engineering mathematics course (for juniors), and the transport phenomena course (offered to seniors).

We offer the course twice a year and it has an average student enrollment of twelve. The students are usually divided into three groups. The objectives of the course are to engage each student in active participation and experimentation and to have them analyze statistically the experimental data with the aid of a computer, to perform necessary calculations for tables and figures, and to prepare a written report using a word processor.

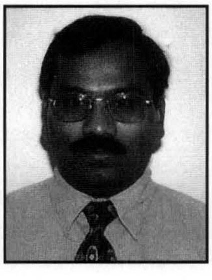
In this paper we will describe several experiments for measuring the viscosity of aqueous glycerol solutions using a tank-tube viscometer. Measuring the viscosity of highly viscous liquids with the tank-tube viscometer is easier than using other types of viscometers. This inexpensive viscometer generates numerous reproducible viscosity data of highly viscous aqueous glycerol solutions under given experimental conditions. The tank-tube viscometer consists of a large-diameter reservoir and a long, small-diameter, vertical tube.

Fabrication of the tank-tube viscometer is inexpensive since it does not need ancillary equipment such as a high-pressure pump, a pressure transducer, or an accurate flow meter. Our viscosity experiment provides an opportunity for students to apply mathematical and computational skills to analyzing statistically experimental data and to write a report using computer software. Mathematical and computational skills are learned through the mathematics courses as well as the basic engineering courses that are offered to our freshman and sophomore students. Our experiment also familiarizes students with the concept of viscosity of highly viscous Newtonian fluids, which they learned in the lecture class of the fluid mechanics course.

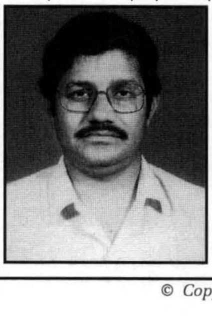
The main objective of the experiment is to demonstrate the effects of water concentration as well as temperature on viscosity by applying experimental data of accumulated amounts of aqueous glycerol solutions at various drain dura-



***K. C. Kwon** is Professor of Chemical Engineering at Tuskegee University. He received his BS from Hanyang University, Seoul, Korea, his MS from University of Denver, and his Ph.D from Colorado School of Mines. His industrial experience includes five years as a process engineer at the synthetic fuel division of Gulf Oil Company, Tacoma, Washington. His research interests include reaction kinetics, coal conversion, adsorption separation, metal oxide sorbents and transport properties.*



***S. Pallerla** is Assistant Professor of Chemical Engineering at Tuskegee University. He received his BS from Osmania University, Hyderabad, India, his MS from the Indian Institute of Technology-Madras and his PhD from Auburn University. His research interests include environmental biotechnology, bioprocessing, kinetics, adsorption and pulp and paper engineering.*



***Sanjeev R. Roy** is working in Chemical/Environmental Engineering at Tuskegee University. He received his BS from Birla Institute of Technology, India, and his MS from Tuskegee University. He has worked as Executive Engineer for Oil & Natural Gas Corporation India for nine years. His research interests includes innovative approach to system design.*

The experiment is designed as an extension of the fluid mechanics course (offered to sophomore students), the engineering mathematics course (for juniors), and the transport phenomena course (offered to seniors).

tions to a newly developed viscosity equation for the fabricated tank-tube viscometer. The viscosity equation was developed under the assumptions that both the quasi-steady-state approach and the negligible friction loss due to a sudden contraction between the reservoir tank and the tube are valid.

THEORY

Fluid mechanics is the study of forces and motions in fluids.[1] Treatment of fluid flow required understanding the physical properties of a fluid that affects the motion. The two most important fluid properties are density and viscosity, and the most important physical property of a fluid from the point of view of the study of fluid mechanics is the viscosity.[2] A fluid is a substance that undergoes continuous deformation when subjected to a shear stress; the resistance offered by a real fluid to such deformation is called its viscosity. All fluids have viscosity. This property causes friction.[3] The viscosity of a Newtonian fluid is constant if static pressure and temperature are fixed.

A chemical engineer is concerned with the transport of fluids from one location to another by pumping fluids through pipes over long distances from storage to reactor units.[4] Many intermediate products are pumped from one unit operation to another, and raw materials such as natural gas and petroleum products may be pumped very long distances to domestic or industrial consumers.

These industrial processes require determination of the pressure drops in both the pipeline and the individual units themselves, evaluation of the power required for pumping, and estimation of the most economical sizes of pipes and measurement of the flow rates. The viscosity value of a particular fluid flowing through pipes and individual equipment is an essential property in designing these industrial processes.

Viscosity values of a Newtonian fluid can be calculated using

$$\ell n\left(\frac{H+L}{h+L}\right)=\left(\frac{gR_o^4\rho}{8\mu R^2 L}\right)t \tag{1}$$

if levels of a liquid in a reservoir tank of a tank-tube viscometer[5] at different drain durations are known. Equation (1) is developed based on the assumptions that both the quasi-steady-state approach and the negligible friction loss due to a sudden contraction between the reservoir tank and the tube are valid.

The change in the level of a highly viscous liquid in the reservoir tank at a given drain duration is very small, however. Often it is difficult to read the change in the level of the liquid in the reservoir. Hence, the liquid level at a given duration of time is described in terms of accumulated amounts of the liquid drained from the reservoir tank (see Eq. 2). A mass balance of the liquid around the reservoir tank of the tank-tube viscometer produces

$$h = H - \frac{m}{\pi R^2 \rho} \tag{2}$$

We then obtain

$$-\ell n\left(1-\frac{m}{(H+L)\pi R^2\rho}\right)=\left(\frac{gR_o^4\rho}{8\mu R^2 L}\right)t \tag{3}$$

by substituting the "h" value from Eq. (2) into Eq. (1). The left-hand side of Eq. (3) contains accumulated amounts of the liquid drained from the tank-tube viscometer, while the right-hand side contains drain durations. Therefore, Eq. (3) allows us to calculate the liquid viscosity if the total mass of the liquid out of the reservoir at a given drain duration is known.

The left-hand side of Eq. (3) is denoted as Y, as shown by

$$Y = -\ell n\left(1-\frac{m}{(H+L)\pi R^2\rho}\right) \tag{4}$$

The Y values of Eq. (4) are easily calculated by substituting both the amounts of aqueous glycerol solutions drained from the tank-tube viscometer and their density values. Densities of aqueous glycerol solutions were obtained with a densimeter. The "H" value in Eq. (3) is the same as the height of the reservoir when the reservoir tank is filled with a liquid. In this laboratory experiment, the reservoir is filled with aqueous glycerol solutions to avoid measuring the initial level of aqueous glycerol solutions in the reservoir. Otherwise, a possible experimental error source will be added to the experiment by measuring an initial level of aqueous glycerol solutions in the reservoir.

Equation (3) can be simplified to obtain

$$\left(\frac{m}{(H+L)\pi R^2\rho}\right)\cong\left(\frac{gR_o^4\rho}{8\mu R^2 L}\right)t \tag{5}$$

if the length of the vertical tube of the tank-tube viscometer is relatively longer than the initial level of a liquid in the reservoir and if amounts of the liquid drained from the reservoir are relatively small.

The viscosity of liquids decreases with increasing tem perature. An approximate empirical observation for the temperature dependency of viscosity for liquids is described by

$$\mu = Ae^{(B/RT)} \tag{6}$$

where A and B are empirical constants. This equation can be used with viscosity data for interpolation or modest extrapolation.[6] Since liquids are essentially incompressible, the viscosity of liquids is not affected by pressure.[7]

An average velocity equation for liquid flow in the vertical tube of the tank-tube viscometer is described as a function of accumulated amounts of aqueous glycerol solutions drained at a given drain duration. Combining the average velocity equation

$$v_m = \frac{\rho g R_o^2}{8\mu L}\left(H + L - \frac{m}{\pi R^2 \rho}\right) \tag{7}$$

with Eq. (3) gives

$$v_m = -\left(\frac{R}{R_o}\right)^2 \left[\ell n\left(1 - \frac{m}{\pi R^2 \rho (H+L)}\right)\right]\left(H + L - \frac{m}{\pi R^2 \rho}\right)\frac{1}{t} \tag{8}$$

... we will describe several experiments for measuring the viscosity of aqueous glycerol solutions using a tank-tube viscometer. ... This inexpensive viscometer generates numerous reproducible viscosity data of highly viscous aqueous glycerol solutions under given experimental conditions.

EXPERIMENTAL SETUP

A wide variety of viscometers (capillary, glass-tube, rotational, falling-ball, cup, and oscillatory[8]) is available for measuring viscosity. An inexpensive viscometer, the so-called tank-tube viscometer, was fabricated for the course (see Figure 1). It consists of a cylindrical reservoir and a long vertical tube. The radius and the height of the reservoir are 2.5531 cm and 14.7 cm, respectively. The radius and length are 0.1637 cm and 73.8 cm, respectively.

The reservoir is made of a transparent Plexiglas pipe, whereas the tube of the viscometer is made of stainless steel. The vertical tube is connected at the bottom of the reservoir. Aqueous glycerol solutions are chosen to test the fabricated tank-tube viscometer since glycerol is completely soluble in water, very viscous, and does not inflict any health hazards.[9] The bottom end of the vertical tube is initially closed with a rubber bulb and aqueous glycerol solutions are fed to the reservoir. An electronic balance placed beneath the bottom end of the vertical tube is used to measure accumulated amounts of aqueous glycerol solutions drained from the reservoir at a given drain duration.

EXPERIMENTAL PROCEDURE

The tank-tube viscometer is set up by placing an electronic balance beneath the bottom end of its vertical tube in a constant-temperature chamber, as shown in Figure 1. The cylindrical reservoir tank is filled with an aqueous glycerol solution that is allowed to flow through the vertical tube. When the vertical tube is filled with the aqueous glycerol solution by evacuating air from it, its bottom end is closed with a rubber bulb to stop the flow of solution. After closing

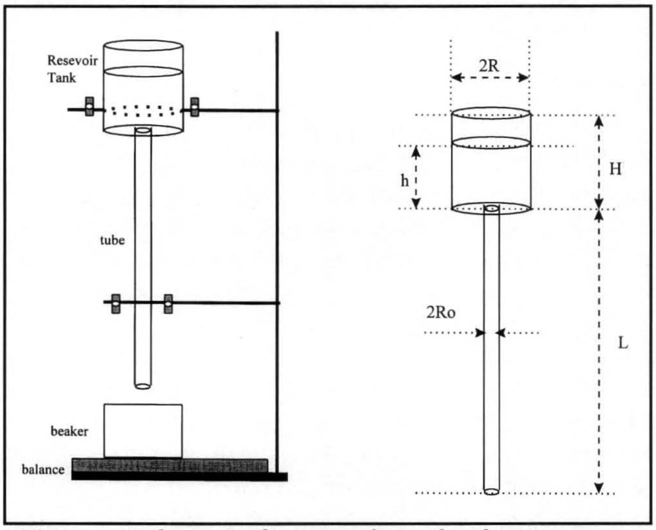


Figure 1. Schematic diagram of a tank-tube viscometer.

its bottom end, the cylindrical reservoir tank is again filled with the aqueous glycerol solution. Consequently, measurement of the initial level of the solution in the reservoir is not necessary since the it is equal to the height of the reservoir itself. The height of the reservoir is incorporated into Eq. (3).

An empty receiving beaker is placed on the electronic balance and tared. Reading accumulated amounts of aqueous glycerol solutions off the LSD digital indicator of the electronic balance starts when the rubber bulb from the bottom end of the tube is removed to allow the solution to flow into the beaker.

Accumulated amounts of aqueous glycerol solutions drained from the viscometer at random drain durations are read off the electronic balance, using a stopwatch. After the tank-tube viscometer is rinsed with distilled water for the next experiment, the reservoir tank is dried with paper towels and the vertical tube is dried with acetone.

ANALYSIS OF EXPERIMENTAL DATA

Experimental data of accumulated amounts of an aqueous glycerol solution drained from the reservoir of a tank-tube viscometer at various drain durations are obtained by using an electronic balance and a stopwatch. Several experimental data for aqueous glycerol solutions were obtained under controlled experimental conditions, such as concentrations of water in aqueous glycerol solutions and temperatures of aqueous glycerol solutions.

Each group of students obtained four different viscosity values of aqueous glycerol solutions with four different water contents at a controlled temperature during a 3-hour laboratory session. These experiments provide opportunities for students to learn the effects of water concentrations in aqueous glycerol solutions on viscosity values. Experimental results (performed at three different temperatures by three groups) are gathered and plotted after a complete rotation of this laboratory experiment to each group. These experimental results also provide opportunities for students to learn effects of temperature of aqueous glycerol solutions on viscosity values.

Personal computers, loaded with a FORTRAN program and Microsoft Professional Office, are used to process several series of experimental data of amounts of aqueous glycerol solutions drained from the reservoir at various drain durations. These data are applied to Eqs. (3) and (8) to calculate viscosity values and average velocity values with the aid of the FORTRAN program. Figures 2 through 8 are plotted using Microsoft Excel.

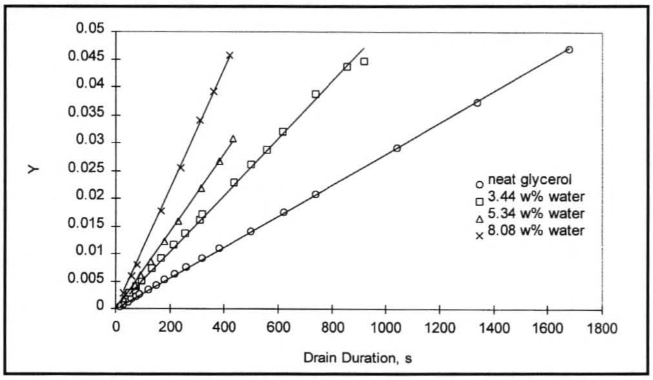


Figure 2. *Values of the left-hand side (LHS) of Eq. (3) at various drain durations and 27°C.*

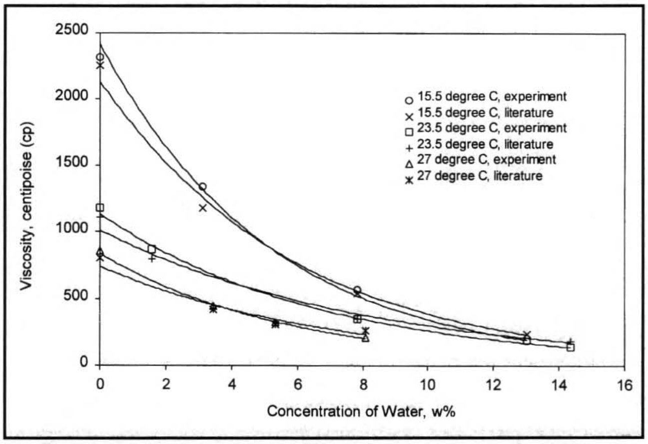


Figure 3. *Comparison of viscosity values of aqueous glycerol solutions at various temperatures from the experiment with those from the literature.*

A slope of the best-fit straight line passing through the origin of the rectangular coordinates is obtained through the linear least-squares method. A viscosity value is calculated by substituting a density value of aqueous glycerol solutions, the diameters of both the reservoir tank and the vertical tube, and the length of the vertical tube into the slope value (see Eq. 4). Consequently, these computations provide an opportunity for students to process experimental data with the aid of personal computers loaded with necessary computer software.

Students also obtain the slope values of the best-fit straight lines, their correlation coefficients, and their viscosity values using their hand calculators, rather than personal computers, when preparing a model calculation section of a laboratory report. The computer-generated data were used to examine whether or not their hand calculations were correct. As a result, they were able to enhance their computational skills. Computations by hand calculators also help students solve the written problems of a final examination since the answers to its problems are obtained with hand calculators.

A detailed derivation of Eqs. (3), (5), and (8) is discussed in the senior transport phenomena class, using the mathematical skills learned from the mathematics courses. Equation (3) is derived assuming that the quasi-steady-state approach and the negligible friction loss due to a sudden contraction between the reservoir tank and the tube are valid. Validity of the quasi-steady-state assumption is discussed in the transport phenomena class and the chemical reaction engineering classes by presenting the experimental results on viscosity of aqueous glycerol solutions. Deviation range of viscosity values obtained from the approximate equation (Eq. 5) from those from Eq. (3) is discussed in the engineering mathematics class by presenting the experimental results of this experiment.

Students prepare a report using a word processor. A typical laboratory report includes several sections, such as an abstract, an introduction, theory, the experimental set-up, experimental procedures, calculations, results, discussion, and conclusions. Figures and tables generated from a laboratory experiment and a schematic diagram on an experimental set-up are also include in the report. Figures and the schematic diagram must be drawn with the aid of computer software, whereas the calculation section should be handwritten.

RESULTS AND DISCUSSION

Left-hand side values of Eq. (4) are obtained with accumulated amounts of an aqueous glycerol solution drained from the reservoir at various drain durations, which are plotted against drain durations (see Figure 2). The slope of the best-fit line is obtained through the linear least-squares method. The viscosity value is calculated from the slope of the best-fit line by substituting the density value of the aqueous glycerol solution as well as the sizes of the viscometer into the right-hand side of Eq. (3). The sizes of the viscometer include the radius of the reservoir and the diameter and the length of the vertical tube.

The slope of this plot increases with increased concentrations of water in the aqueous glycerol solution. This observation shows that the viscosity of aqueous glycerol solutions decreases with increased concentrations of water. A good linear relationship between Y values and drain durations (see Figure 2) may indicate that the assumptions made in developing the viscosity equation for a tank-tube viscometer are valid.

Viscosity values of aqueous glycerol solutions obtained from this experiment are compared with those from the literature at various concentrations and temperatures (see Figure 3). The values obtained from this experiment are in agreement with those from the literature[10] over the range of water concentration and temperature explored, with an average deviation of 3.8% (see Figure 3). These observations also suggest that the validity of the assumptions made in developing the viscosity equation for a tank-tube viscometer are justified.

Viscosity values of aqueous glycerol solutions are plotted against concentrations of water in aqueous glycerol solutions at various temperatures (Figure 3). Viscosity values decrease drastically at relatively low concentrations (below 8 wt %) of water in aqueous glycerol solutions, while viscosity values decrease moderately at relatively high concentrations (above 8 wt %) of water.

Viscosity values are a strong function of temperature at relatively low concentrations (below 8 wt %) of water in aqueous glycerol solutions, whereas viscosity values are a moderate function of temperature at relatively high concentrations (above 8 wt %).

A series of viscosity values of neat glycerol at various temperatures is applied to Eq. (6) to find the Arrhenius relationship between viscosity values and temperatures of aqueous glycerol solutions (see Figure 4). A very good Arrhenius relationship

$$\mu = 1.4618 \times 10^{-8} e^{(7439/T)} \tag{9}$$

is obtained over the temperature range of 15 to 27°C with a correlation coefficient value of 0.99.

Each viscosity value of aqueous glycerol solutions at its random drain duration is calculated using Eq. (3). This viscosity value is plotted against its accumulated amount of aqueous glycerol solution drained from the viscometer at random drain durations (see Figure 5). Viscosity values appear to be independent of accumulated amounts of aqueous glycerol solution drained at various drain durations. These results show that the solutions are Newtonian fluids and reproducibility of viscosity values of aqueous glycerol solutions obtained from the viscosity equation of the tank-tube viscometer appear to be excellent.

Viscosity values of aqueous glycerol solutions calculated with the approximate equation (Eq. 5) are compared with those from Eq. (3). Deviation percentages of viscosity values obtained from Eq. (5) in reference to those from Eq. (3)

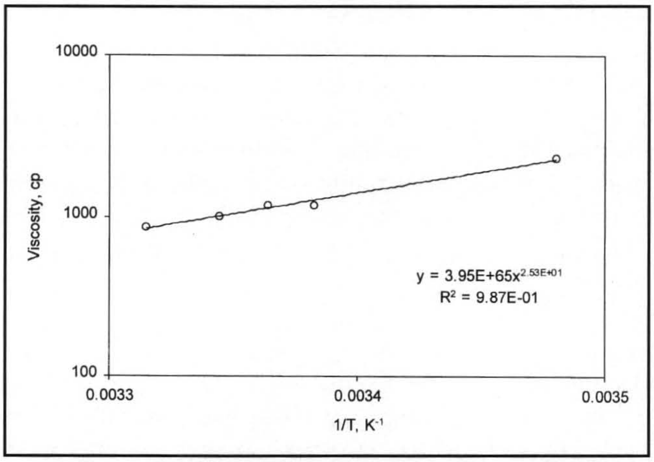


Figure 4. *Effects of temperature on viscosity of neat glycerol.*

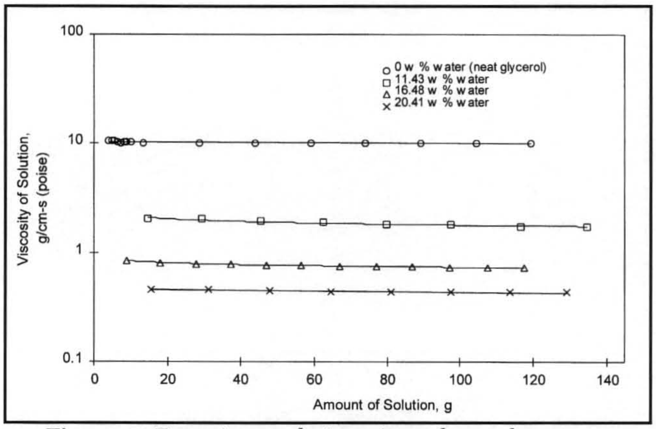


Figure 5. *Experimental viscosity values of aqueous glycerol solutions plotted against accumulated amounts of solution drained at 24.9°C.*

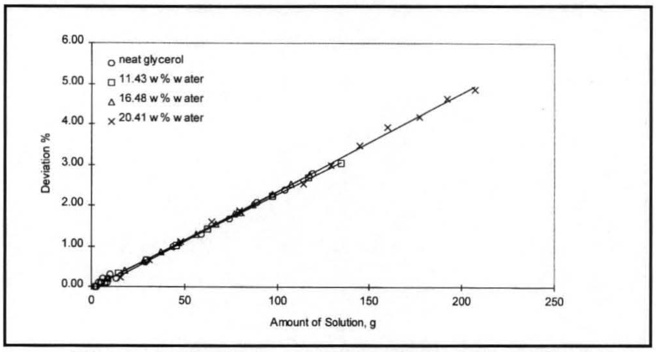


Figure 6. *Deviation percent of viscosity values obtained from Eq. (5) in comparison with those from Eq. (3) at 24.9°C.*

are evaluated at random drain duration. Deviation percentages increase with amounts of aqueous glycerol solutions drained from the tank-tube viscometer (see Figure 6) with a deviation range of 0 to 5%. Deviation percentages appear to be independent of water concentrations in aqueous glycerol solutions over the water concentration range from 0 to 20%. The maximum deviation error is 8.56% when the reservoir tank filled with aqueous glycerol solutions is completely drained.

Average velocities for flow of aqueous glycerol solutions in the vertical tube of the tank-tube viscometer are calculated at 24.9°C, using Eq. (8). Average velocities of aqueous glycerol solutions increase with increased water concentrations (see Figures 7 and 8). The standard deviation of average velocities decreases with decreased water concentrations over the drain duration range of 10 to 250 seconds. The mean values of average velocities and their standard deviations for the 20.41-, the 16.48-, and the 11.43-wt%-water glycerol solution, and the neat glycerol are 10.25±0.17 cm/s, 6.06±0.16 cm/s, 2.49±0.11 cm/s, and 0.468±0.024 cm/s, respectively. These observations may indicate that validity of the quasi steady-state approach is justified for the derivation of the viscosity equation of the tank-tube viscometer.

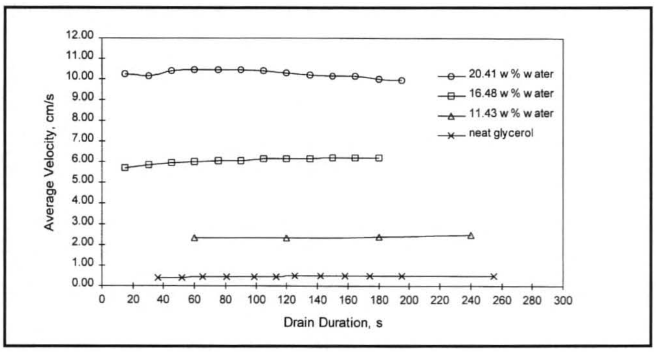


Figure 7. *Average velocity of aqueous glycerol solutions in the vertical tube of the tank-tube viscometer against various drain durations at 24.9°C.*

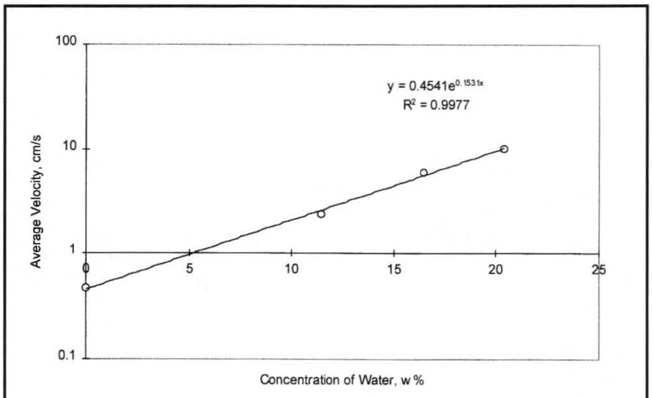


Figure 8. *Average velocity against various water concentrations in aqueous glycerol solutions at 24.9°C.*

CONCLUSIONS

An inexpensive tank-tube viscometer was fabricated to determine viscosity of highly viscous aqueous glycerol solutions, and a viscosity equation of a tank-tube viscometer was developed to calculate the viscosity of the solutions. This experiment introduces chemical engineering students to the concept of viscosity of a Newtonian fluid in fluid mechanics. It also provides an opportunity for the students to carry out experiments for the acquisition of experimental data, to apply their mathematical and computational skills as well as statistical analysis to interpreting experimental data with the aid of computer software, to survey the literature on viscosity, and to write a laboratory report using a word processor.

NOMENCLATURE

cp centipoise
g acceleration of gravity
h level of a liquid in a reservoir tank at a drain duration t
H initial level of a liquid in a reservoir tank or height of a reservoir tank when the reservoir tank is filled
L length of a vertical tube
LHS left-hand side values of Eq. (3)
m accumulated amount of a liquid drained at t
R inside radius of a cylindrical reservoir tank
R_o inside radius of a vertical tube
t drain duration
T temperature of aqueous glycerol solutions, K
v_m average velocity of a fluid flow in a vertical tube
Y left-hand side value of Eq. (3)
μ viscosity of aqueous glycerol solutions
ρ density of aqueous glycerol solutions

ACKNOWLEDGMENTS

The authors thank Drs. Nader Vahdat and Dennis Liken for comments and suggestions on this paper.

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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@engin.umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

RATE MEASUREMENT WITH A LABORATORY-SCALE TUBULAR REACTOR

Wei-Yin Chen
University of Mississippi • University, MS 38677-9740

Electrically heated tubular flow reactors have been commonly used for rate measurement in research laboratories. Questions often arise concerning the effect of velocity profile, axial and radial molecular diffusions, and axial temperature distribution on the measured conversion and estimated rate. Analysis of reactors of this type can be a fruitful area for homework for a reaction engineering course. Two home problems are offered in this article; both are aimed at measurement of reaction rate of nitrogen oxide and char with a flow reactor of commonly adopted size.

The first problem justifies the use of conversion data from a laminar flow reactor for rate estimation. In a laminar tubular flow system without reaction, the concentration of a gaseous species, C, can be described to a two-dimensional dispersion model, *i.e.*

$$\frac{\partial C}{\partial t} = D_M \frac{\partial^2 C}{\partial z^2} + D_M\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r}\right) - u_0\left(1 - \frac{r^2}{R^2}\right)\frac{\partial C}{\partial z} \quad (1)$$

where D_M represents the molecular diffusivity of the species of interest, and u_0 is the maximum centerline velocity. The analyses by Taylor,[1,2] Aris,[3] and Hunt[4] demonstrated that, under a specific criterion, Eq. (1) reduces to an axial-dispersed, plug-flow model, or

$$\frac{\partial C}{\partial t} = E_z \frac{\partial^2 C}{\partial z^2} - u\frac{\partial C}{\partial z} \quad (2)$$

where u is the mean fluid velocity and E_z is the effective axial dispersion coefficient, or the sum of molecular diffusivity and the apparent diffusivity contributed by the laminar velocity profile, *i.e.*

$$E_z = D_M + \frac{R^2 u^2}{48\, D_M} \quad (3)$$

Equations (2) and (3) have been derived assuming that the radial mixing is great enough compared to the longitudinal convective mixing to ensure a uniform cross-sectional concentration. Mathematically, this criterion implies a small radial Peclet number, Pe_r, or

Wei-Yin Chen *is Associate Professor of Chemical Engineering at the University of Mississippi. His teaching and research interests have been in reaction engineering and mathematical modeling. He received a PhD in Chemical Engineering from the City University of New York, an MS in Chemical Engineering from the Polytechnic Instutute of New York, an MS in Applied Mathematics and Statistics from the State University of New York at Stony Brook, and a BS in Chemical Engineering from Tunghai University.*

$$\frac{1}{Pe_r} = \frac{D_M}{uR} >> \frac{R}{16\,L} \tag{4}$$

where L is the length of the tube.

For a laminar-flow reactor involving a first-order chemical reaction and back mixing, the full description of the reacting system involves an additional reaction term in Eq. (1). Wissler[5] demonstrated that the Taylor-Aris model remains valid, *i.e.,* Eqs. (3) and (4) remain the basis for

$$\frac{\partial C}{\partial t} = E_z \frac{\partial^2 C}{\partial \partial z^2} - u\frac{\partial C}{\partial z} + kC \tag{5}$$

provided that the reaction rate, k, satisfies the condition

$$\frac{kR^2}{\left(3.8^2\, D_M\right)} < 1 \tag{6}$$

At steady state, Eq. (5) has been solved by Wehner and Wilhelm.[6] For small $E_z/(uL)$, their solution after dropping higher-order terms in its series expansion becomes

$$1 - X = \exp\left[-kt + (kt)^2 \frac{E_z}{uL}\right] \tag{7}$$

where X is the conversion. The second factor in the above exponential term represents the deviation of the dispersion model, Eq. (5), from a plug-flow reactor.

The second problem investigates the effect of axial temperature variation on the estimation of intrinsic rate. In a tubular reactor heated by a single heating element of uniform resistance, reacting gas travels successively through heating, isothermal, and cooling sections, and rate estimation requires analysis of conversions in all three stages. Using an experimentally measured wall temperature distribution and a heat-transfer algorithm established by Sellars, *et al.,*[7] it is possible to calculate the average gas temperature over a particular cross-sectional area of the tubular flow (see Figure 1). The predicted distribution indicates that, for a reactor equipped with a 30.5-cm-long heating element, each nonisothermal section has about the same length as the isothermal section. Since the gas travels slower and has a longer residence time in these nonisothermal sections, the rate estimation should take into consideration the conversions in these two sections. Problem 2 addresses this issue and seeks to recover the intrinsic rate of NO/char reaction and mass-transfer limitations. To simplify the calculation, the gas temperatures in the two nonisothermal sections are approximated by two constant heating-rate profiles. It is also demonstrated that, while this type of analysis traditionally requires extensive effort on trial and error, it can be conveniently solved now by contemporary software such as MathCad.

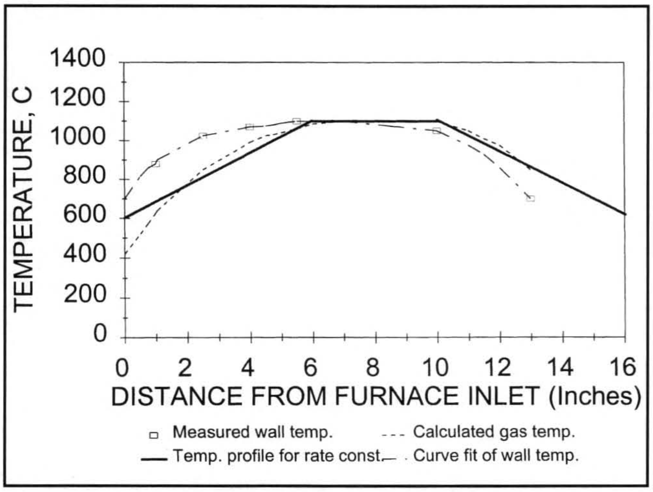

Figure 1. *Measured wall temperature, calculated gas temperature based on Sellars,* et al.,*[7] and simplified three-zone temperature profile for kinetic analysis.*

PROBLEM 1

An electrically heated tubular reactor with an I.D. of 1.91 cm and a heated length of 30.5 cm is used for measuring the rate of NO/char reaction. Products of the reaction are N_2, CO, and CO_2. The feed at 1 atm contains 1000 ppm of NO and char particles in a helium base. Using the heat transfer algorithm of Sellars, *et al.,*[7] and an experimentally measured temperature distribution, the axial gas temperature distribution is calculated (see Figure 1); in the central segment of the reactor the gas reaches 1100°C for about 10 cm. Well-dispersed char particles in the reacting gas are fed vertically downwards into the reactor at 25°C at a volumetric flow rate of 2000 cm^3/min. Data collected from this reactor indicate that the NO disappearance rate is first order with respect to the NO concentration, and the NO conversions are always below 95% if a proper char feeding rate is chosen.

> ***1.*** *Using the Taylor-Aris[1-3] criterion, determine if an axial-dispersed, plug-flow model is appropriate for the approximation of gas concentration in a laminar flow system similar to that discussed above but containing no chemical reaction. If so, determine the effective diffusivity.*
>
> ***2.*** *Using the Wissler[5] criterion, determine if the axial-dispersed, plug-flow model (Eq. 5) can be used for estimating the rate of the NO/char reaction.*
>
> ***3.*** *Using the solution of Wehner and Wilhelm,[6] conclude if it is pertinent to use the plug-flow reactor model without dispersion for estimating the reaction rate.*

Solution

1. A laminar flow system without chemical reaction can be approximated by an axial-dispersed, plug-flow model when Eq. (4) is satisfied or the radial Peclet number, $Pe_r(=uR/D_M)$, is small. At 1100°C, the flow rate and average residence

time of gas in the isothermal section of the reactor are 153.6 cm^3s^{-1} and 0.2 s, respectively. The diffusivity of NO in He can be estimated, based on molecular theory,[8] as

$$\frac{PD_{AB}}{(P_{cA}P_{cB})^{\frac{1}{3}}(T_{cA}T_{cB})^{\frac{5}{12}}\left(\frac{1}{M_A}+\frac{1}{M_B}\right)^{\frac{1}{2}}} = a\left(\frac{T}{\sqrt{T_{cA}T_{cB}}}\right)^b \quad (8)$$

where

D_{AB} cm^2sec^{-1}
P atm
T K
a 2.745×10^{-4}
b 1.823

This formula suggests $D_{AB} = 13.7\ cm^2s^{-1}$ at 1100°C. By resorting to the Chapman-Enskog kinetic theory (see Problem 2), $D_{AB} = 8.1\ cm^2s^{-1}$. Variations of diffusivity in this range do not change the conclusions to be discussed below. Based on the system parameters obtained above, the radial Peclet number at 1100°C and dimensionless term on the right-hand side of Eq. (4) are estimated as

$$\frac{1}{Pe_r} = \frac{D_M}{Ru} = 0.288 \quad \text{and} \quad \frac{R}{16L} = 0.00597 \quad (9)$$

Thus, the Taylor-Aris criterion, Eq. (4), is satisfied, and by resorting to Eq. (3), the effective axial dispersion coefficient is

$$E_z = D_M + \frac{R^2u^2}{48\,D_M} = 17.1\frac{cm^2}{s} \quad (10)$$

2. Wissler's criterion gives the range of k for adopting the dispersion model, Eq. (5), as

$$\frac{kR^2}{(3.8)^2 D_M} < 1 \quad \text{or} \quad k < 216\ s^{-1} \quad (11)$$

This condition corresponds to an extremely fast rate or a nearly complete conversion, specifically

$$1 - X = \frac{[NO]_{out}}{[NO]_{in}} = e^{-kt} = 10^{-19} \quad (12)$$

Since NO conversions from the reactor have always been below 95%, Wissler's criterion is satisfied.

3. At a high conversion, *e.g.,* X=0.95, and a reaction time t=0.2s, Eq. (12) gives the rate from a plug-flow reactor without dispersion, or $k=15.0\ s^{-1}$.The reciprocal value of the effective axial Peclet number is $1/Pe_z = E_z/uL = 3.38 \times 10^{-2}$. This small number implies only a small deviation from the assumption of zero dispersion. Specifically, resorting to the solution of Wehner and Wilhelm, or Eq. (7), we obtain the rate under the influence of dispersion, $k = 16.9\ s^{-1}$. Thus, the assumption of zero dispersion leads to a maximum error of about 13% at X = 0.95; this error is lower at lower conversions (4.4% at X=0.70 and 2.5% at X = 0.50).

PROBLEM 2

While Problem 1 justifies the use of a plug-flow reactor model for rate estimation, this problem seeks to study the effect of the two nonisothermal sections of the flow on measuring the intrisic rate of NO reaction with char.

1. Assuming the reaction is important only in the 10-cm isothermal region and the reaction is free from internal and external mass-transfer limitations, derive a design equation that relates reaction rate to experimentally observed NO conversion, internal surface area of char, char feeding rate, and residence time. The first-order reaction rate of NO on char surface can be expressed as

$$r_{NO} = -kAP_{NO} \quad (13)$$

where

r_{NO} rate of NO formation, moles s^{-1} (g of char)$^{-1}$
A specific, internal surface area of char, m^2g^{-1}
P_{NO} partial pressure of NO, atm
k rate constant, moles $s^{-1}m^{-2}atm^{-1}$

2. Redo Part 1 of the problem assuming the conversions in the two nonisothermal regions of the reactor are not negligible and can be approximated by two constant heating-rate profile (see Figure 1).

3. Assuming the internal mass-transfer limitation cannot be ignored, estimate the frequency factor, activation energy, Thiele modulus, and effectiveness factor in a three-zone reactor as described in Part 2. For a reactive char derived from lignite under mild pyrolysis conditions, the following data are given:

conversion at 1100°C: 0.875
conversion at 1000°C: 0.815
mean particle radius: 0.0064 cm
char internal surface area, A: 255 m^2g^{-1}
char feeding rate, W_1: 1.067×10^{-3} g min^{-1}
bulk density of char: 1.2 g cm^{-3}
pore volume: 0.07 cm^3g^{-1}

4. Estimate the external mass-transfer limitation.

Solution

1. *Conversion in the Isothermal Region* • A molar balance over a small section of tubular reactor yields[9]

$$F_{NO} + dF_{NO} = F_{NO} + (r_{NO})dW_t \quad (14)$$

where W_t is the char weight in the isothermal region and F_{NO} is the molar flow rate of NO. By the definition of conversion, X, we obtain

$$dF_{NO} \equiv d\left[F_{NO,in}(1-X)\right] = -F_{NO,in}dX = +F_{NO,in}d\left(\frac{P_{NO}}{P_{NO,in}}\right) \quad (15)$$

Substituting Eqs. (13) and (14) into Eq. (15) and integrating gives

$$\ell n(1-X) = \ell n\frac{P_{NO}}{P_{NO,in}} = \frac{-kAW_tP_{NO,in}}{F_{NO,in}} \quad (16)$$

Furthermore, the molar flow rate of an ideal gas mixture can be expressed as

$$F_{NO,in} = \frac{P_{NO,in}}{P}\frac{v}{2.445\times10^4} \quad (17)$$

where the constant in the denominator denotes the specific volume of an ideal gas at 25°C in cm^3 $mole^{-1}$, and v is the total inlet volumetric flow rate measured at 25°C in cm^3s^{-1}. The char weight in the reactor, W_t, in Eq. (16) can be expressed in terms of char feeding rate, W_1, through the relation W_t=W_1t_h, where W_1 is in g s^{-1} and t_h the residence time in the isothermal section in s. Substituting the relation and Eq. (17) into Eq. (16), with P=1 atm and v=33.33 cm^3s^{-1}, we obtain

$$\ell n(1-X) = \frac{-2.445\times10^4 kAW_1t_h}{33.33} = -7.34\times10^2 kAW_1t_h \quad (18)$$

This expression can be used in the estimation of reaction rate, k, if only the conversion in the isothermal region is important.

2. *Conversion in the Nonisothermal Regions* • For an ideal gas, the gas residence time t, in s, can be expressed as a function of temperature and distance traveled

$$dt = \frac{a}{G}dz = 25.62\frac{1}{T}dz \quad (19)$$

where

- a cross-sectional area of the reactor tube, cm^2
- G gas volumetric flow rate, cm^3s^{-1}
- z longitudinal distance of gas traveled in the tubular reactor, cm
- T gas temperature in the tube, K

During the heating and cooling periods, the estimated gas temperature is approximated by two linear temperature profiles, as shown in Figure 1. Specifically, since the gas temperature varies from 700 to 1100°C in 11.9 cm, the heating rate can be characterized as dT/dz=±33.51°C/cm. Substituting this expression into Eq. (19), we obtain

$$dt = \pm\frac{0.765}{T}dT \quad (20)$$

From a material balance, *i.e.,* Eqs. (13) through (15), we have

$$\frac{dP_{NO}}{P_{NO}} = \frac{-kAP_{NO,in}dW}{F_{NO,in}} \quad (21)$$

Substituting Eqs. (17) and (20) into Eq. (21) and integrating the resultant expression over the heating, isothermal, and cooling sections, we obtain

$$\ell n(1-X) = 733.6\left(-\int\frac{0.765}{T}W_1Ak_0e^{-\frac{E_a}{RT}}dT - t_hW_1Ak_0e^{-\frac{E_a}{RT}} - \int-\frac{0.765}{T}W_1Ak_0e^{-\frac{E_a}{RT}}dT\right) \quad (22)$$

where k_0 and E_a are the preexponential factor and the activation energy. The two unknowns in Eq. (22), k_0 and E_a, can be estimated by implementing it twice for two sets of temperature/conversion data. Numerically, this set of two equations can be conveniently solved with MathCad. A temperature at which the reaction is slow, *e.g.,* 600°C, can be chosen as the lower integration limit. This procedure can be repeated for data collected over a wide range of temperatures so that linear regression can be conducted and the average k_0 and E_a can be obtained.

3. *Internal Mass Transfer Limitation* • To investigate the extent of internal mass transfer limitation, the observed Arrhenius rate in the last section can be considered the product of the intrinsic surface reaction rate and the effectiveness factor, η, *i.e.,* from Eq. (22)

$$\ell n(1-X) = 733.6\left(-\int\frac{0.765}{T}W_1A\eta k_0e^{-\frac{E_a}{RT}}dT - t_hW_1A\eta k_0e^{-\frac{E_a}{RT}} - \int-\frac{0.765}{T}W_1A\eta k_0e^{-\frac{E_a}{RT}}dT\right) \quad (23)$$

The effectiveness factor is a function of the Thiele modulus, ϕ,[10] *i.e.,*

$$\eta = \frac{3}{\phi}\left(\frac{1}{\tanh\phi} - \frac{1}{\phi}\right) \quad (24)$$

where the Thiele modules is defined as

$$\phi = R\left(\frac{akA\rho_p}{D_{eff}}\right)^{0.5} \quad (25)$$

and

- R radius of char particles, cm
- a molar volume of an ideal gas, 2.445×10^4, cm^3 $mole^{-1}$
- D_{eff} effective diffusion coefficiency, cm^2s^{-1}
- ρ_p bulk density of char, g cm^{-3}

The reciprocal of the effective diffusivity can be considered a linear combination of the resistances contributed by the Knudsen and the bulk diffusivity[10]

$$\frac{1}{D_{eff}}=\frac{1}{D_{k,eff}}+\frac{1}{D_{12,eff}} \tag{26}$$

$$D_{k,eff}=19400\left(\frac{\theta^2}{T_m A \rho_p}\right)\left(\frac{T}{M}\right)^{0.5} \tag{27}$$

$$D_{12,eff}=\frac{0.001858^{1.5}\left(\frac{M_1+M_2}{M_1 M_2}\right)^{0.5}}{P\sigma_{12}^2\Omega_D} \tag{28}$$

where

$D_{k,eff}$ Knudsen diffusion coefficient for a porous solid, cm^2s^{-1}
$D_{12,eff}$ bulk diffusion coefficient of species 1 in species 2, cm^2s^{-1}
θ particle void fraction
τ_m tortuosity factor based on the mean pore radius, assumed 2
M_1,M_2 molecular weights of diffusing molecules, M_{NO}=30, M_{HE}=4
M molecular weight of the gas medium
P pressure, 1 atm
Ω_D the "collision integral," a function of $k_B T/\varepsilon_{12}$, dimensionless
ε, σ force constant of the Lenard-Jones potential function, ε in $g\ cm^2s^{-2}$, σ in Å
k_B Boltzmann constant, 1.38×10^{-16} $g\ cm^2s^{-2}K^{-1}$

Equations (26) through (28) allow calculation of the effective diffusivity. The pore fraction can be considered a product of the pore volume and bulk density. Thus, θ = pore volume density = 0.084. From Bird, *et al.*,[8] the parameters for the transport properties can be estimated as

ε_{He}/k_B = 10.2 K, σ_{He} = 2.576 Å
ε_{NO}/k_B = 119 K, σ_{NO} = 3.47 Å
$\sigma_{He\text{-}NO} = 1/2(\sigma_{He}+\sigma_{NO})$ = 3.023 Å
$\varepsilon_{He\text{-}NO} = (\varepsilon_{He}\,\varepsilon_{NO})^{0.5} = 34.84\ k_B g\ cm^2\ sec^{-2}$
$k_B T/\varepsilon_{He\text{-}NO} = 23.83$

$\Omega_D \approx 0.6776$

Substituting these constants into Eqs. (26) through (28), we obtain

$D_{12,eff} = 8.127\ cm^2s^{-1}$
$D_{k,eff} = 3.98 \times 10^{-5}\ cm^2s^{-1}$ for lignite char at 1100°C
$D_{eff} = 3.98 \times 10^{-5}\ cm^2s^{-1}$ for lignite char at 1100 °C

These results show that Knudsen diffusion controls the overall diffusion rate.

Equations (23) through (25) can be solved simultaneously by MathCad for the four unknowns η, ϕ, k_0, and E_a. Equation (23) is implemented twice for two sets of temperature/conversion data in each calculation. The results are: η=0.872, ϕ=1.53, k_0=0.07 moles $s^{-1}m^{-2}atm^{-1}$, and $E_a=3.80 \times 10^3$ cal $mole^{-1}$. The results suggest that internal mass transfer limitation is not negligible in the reacting system. This procedure can be repeated for data collected over a wide range of temperatures so that linear regression can be conducted and the average k_0 and E_a can be obtained.

4. *External Transfer Limitation* • The overall effectiveness factor is defined as

$$\Omega=\frac{\eta}{1+F} \tag{29}$$

where

$$F=\frac{C_g-C_s}{C_s} \tag{30}$$

is an index of external mass-transfer limitations; a large concentration gradient indicates large mass-transfer resistance. In the above expression, C_g=NO concentration in the mainstream of gas flow, in moles cm^{-3}, and C_s=NO concentration at the particle surface, in moles cm^{-3}. Under steady-state conditions, the mass-transfer rate of NO through the boundary layer equals the reaction rate, *i.e.*,

$$k_c S(C_g-C_s)=(-r)W_p \tag{31}$$

where

k_c mass transfer coefficient, cm s^{-1}
S external surface area of a single particle, cm^2
-r reaction rate, moles $g^{-1}s^{-1}$
W_p weight of a single particle, g

NO reduction on the char surface has been expressed as

$$(-r)=\eta k A P_{NO} \tag{32}$$

Assuming the gas is ideal, we have

$$P_{NO}=C_s RT \tag{33}$$

and the weight of a single char particle can be expressed as

$$W_p=\rho_p\frac{1}{6}\pi d_p^3 \tag{34}$$

Substituting Eqs. (31-34) into Eq. (30), we obtain

$$F=\frac{C_g-C_s}{C_s}=\frac{\eta k A R T \rho_p \pi d_p^3}{6 k_c S} \tag{35}$$

Assuming that the particles are entrained in the flow, the mass-transfer coefficient can be estimated based on the Frossling correlation with the Sherwood number (Sh)=2, *i.e.*,

$$k_c=\frac{D_{12}Sh}{d_p}=\frac{2D_{12}}{d_p} \tag{36}$$

where D_{12}=8.127 cm^2s^{-1} (see Eq. 28). The particles have a mean diameter of 0.0128 cm; therefore, from Eq. (36),

$$k_c=1.27\times10^3\,cm\ s^{-1} \tag{37}$$

Substituting this value and the parameters discussed in the last section into Eq. (35), we obtain

$$F=34.34\,\eta k \tag{38}$$

and, from Eq. (29)

$$\Omega=\frac{\eta}{1+34.34\,\eta k} \tag{39}$$

In the parameter-recovery process, Eq. (39) is added into the four-equation set discussed in Part 3, and the resultant five unknowns have been solved by MathCad (see Figure 2). In fact, results from the four-equation model can be used as initial trial values for the five-equation model to warrant convergence and save trial time. For this particular case, we obtain η=0.765, ϕ=2.294, k_0=0.156 moles $s^{-1}m^{-2}atm^{-1}$, E_a=3.80x10^3 cal $mole^{-1}$, and Ω=0.389. The value of Ω is smaller than that of η, suggesting that external mass transfer limitation cannot be ignored for the reactive char chosen in this investigation. At flame temperatures higher than 1100°C, the reaction rate will be higher and the extent of internal and external mass transfer limitations are expected to be even higher.

Figure 2 also contains an estimation of the contributions from the nonisothermal regions, which have the same order of magnitude as the conversion in the isothermal region, emphasizing the importance of including the conversions in the two nonisothermal regions for rate estimation.

$A := 255 \qquad Wt := 1.0667\cdot 10^{-3} \qquad x1 := 0.875 \qquad x2 := 0.815 \qquad T1 := 1373.15$

$T2 := 1273.15 \qquad R := 0.0064 \qquad \eta := 0.865 \qquad \phi := 1.6 \qquad E := 3800$

$k0 := 0.07 \qquad \rho := 1.2 \qquad pv := 0.084 \qquad \Omega := 0.7$

Given

$$Deff := \frac{19400(\rho\cdot pv)^2}{2\cdot A\cdot \rho}\cdot\left(\frac{\frac{T1+T2}{2}}{30}\right)^{0.5}$$

$$\ln(1-x1)=-733.57\cdot A\cdot 0.2\cdot Wt\cdot k0\cdot\left(\Omega\cdot e^{-\frac{E}{1.987T1}}\right)-2\cdot 733.57\cdot\int_{873.15}^{T1}\frac{0.765\cdot Wt\cdot A\cdot\Omega\cdot k0\cdot e^{-\frac{E}{1.987T}}}{T}\,dT$$

$$\ln(1-x2)=-733.57\cdot A\cdot 0.2\cdot Wt\cdot k0\cdot\left(\Omega\cdot e^{-\frac{E}{1.987T2}}\right)-2\cdot 733.57\cdot\int_{873.15}^{T2}\frac{0.765\cdot Wt\cdot A\cdot\Omega\cdot k0\cdot e^{-\frac{E}{1.987T}}}{T}\,dT$$

$$\phi=\left(\frac{2.445\cdot 10^4\cdot k0\cdot e^{-\frac{E}{1.987\frac{T1+T2}{2}}}\cdot A\cdot\rho}{Deff}\right)^{0.5}\cdot R \qquad \eta=\frac{3}{\phi}\cdot\left(\frac{1}{\tanh(\phi)}-\frac{1}{\phi}\right)$$

$$\Omega=\frac{\eta}{1+\eta\cdot\left[k0\cdot e^{-\frac{E}{\left[\frac{1.987(T1+T2)}{2}\right]}}\right]\cdot 34.34}$$

$$\begin{bmatrix}k0\\ \eta\\ \phi\\ E\\ \Omega\end{bmatrix}:=\mathrm{find}(k0,\eta,\phi,E,\Omega)$$

solution of the five unknowns:

$$\begin{bmatrix}k0\\ \eta\\ \phi\\ E\\ \Omega\end{bmatrix}=\begin{bmatrix}0.156\\ 0.765\\ 2.294\\ 3.802\cdot 10^3\\ 0.389\end{bmatrix}$$

Contribution of isothermal region on conversion: $-733.57\cdot A\cdot 0.2\cdot Wt\cdot k0\cdot\left(\eta\cdot e^{-\frac{E}{1.987T1}}\right)=-1.181$

Contribution of nonisothermal region on conversion: $-2\cdot 733.57\cdot\left[\int_{873.15}^{1373.15}\frac{0.765\cdot Wt\cdot A\cdot\eta\cdot k0\cdot e^{-\frac{E}{1.987T}}}{T}\,dT\right]=-2.903$

Figure 2. *Solution of reaction parameters by MathCad. The conversions are assumed to be governed by both internal and external mass transfer limitations and reaction in a three-zone tubular reactor.*

ACKNOWLEDGMENTS

The author wishes to thank the Pittsburgh Energy Technology Center, U.S. Department of Energy, for financial support under grant DE-FG22-93PC93227. Mr. Lin Tang provided valuable assistance to the data collection and calculation during the course of this study.

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HOW TO INVOLVE FACULTY IN EFFECTIVE TEACHING

FRANCESC GIRALT, JOAN HERRERO, MAGDA MEDIR, FRANCESC X. GRAU, JOAN R. ALABART
Universitat Rovira i Virgili de Tarragona • 43006 Tarragona, Catalunya, Spain

The rapid social and economic changes in the world today, triggered by the revolution in communication technologies, is leading to a concept of the "global engineer."[1] Institutional efforts have already begun that will induce and accelerate change in engineering education toward this goal.[2-6] A good example is the ABET EC 2000 criteria in the United States.[3] This concern for a change in higher education also exists in the European Union.[2] The key concern is how engineering schools and departments can obtain and maintain the proactive involvement of faculty in such a change.

The purpose of the paper is to analyze the key factors in achieving involvement and active participation of faculty in the conception and implementation of new and effective teaching strategies. We will analyze the impact that a benchmark in cooperative learning implemented at the introductory level in the chemistry program at Tarragona had on faculty involvement fifteen years ago. We will then go on to identify factors responsible for the decline of the professors' interest in effective teaching when the new five-year ChE undergraduate program was introduced in 1993 and will describe the teaching strategies presently underway to recover the holistic approach to ChE education. These specific and open-ended learning experiences managed by professors and students working together in close collaboration include, at the first year of undergraduate education, development of design projects directed by fourth-year students.

EXAMPLE OF FACULTY INVOLVEMENT

Chemical engineering studies were introduced at Tarragona in 1977 as an Industrial (ICh) option in the five-year chemistry program. Students accessed this ICh option after three years of compulsory education in science and mathematics. Chemical engineering was introduced in the third-year course "Fundamentals of Chemical Engineering." The ICh option included a total of five yearly courses in ChE—one in the fourth year and four in the fifth year—together with three yearly courses in advanced chemistry. The "Fundamentals of Chemical Engineering" course was attended by all students enrolled in the chemistry program. The syllabus included two parts: macroscopic mass and energy balances, and transport phenomena and fluid mechanics.

Chemistry students decided whether to choose the ICh option based on their success in the introductory third-year chemical engineering course. In the early eighties, the number of students enrolled in the ICh option showed a systematic tendency to decrease, and enrollment reached a mini-

Francesc Giralt *is Professor of Chemical Engineering at the University Rovira i Virgili of Tarragona. He received his BSCh from the Institut Químic de Sarrià (Barcelona), his BSChE from the University of Barcelona, his MBA from the ICT (Barcelona), his MASc and PhD from the University of Toronto, and his ScD from the University of Barcelona. His research interests range from experimental and computational transport phenomena to reactor engineering and artificial intelligence.*

Joan Herrero *is Associate Professor of Chemical Engineering at the University Rovira i Virgili of Tarragona, where he has taught for the past decade. He received his BSChE and ScD degrees from the University of Barcelona. His research interests are in transport phenomena and computational fluid dynamics.*

Magda Medir *is Associate Professor of Chemical Engineering and Science Education at the University Rovira i Virgili of Tarragona. She received her BSCh from the Institut Químic de Sarrià, her BSChE from the University of Barcelona, her MASc from the University of Toronto, and her ScD from the University of Barcelona. She directs the Chemical Education for Public Understanding Program in Spain and her research is in the areas of science and engineering education.*

Francesc X. Grau *is Associate Professor of Fluid Mechanics at the University Rovira i Virgili of Tarragona, where he has taught for the past fifteen years. He received his BSChE and his ScD from the University of Barcelona. His research interests focus on experimental and computational fluid dynamics and heat/mass transfer, with applications to environmental and industrial flow problems.*

Joan R. Alabart *has been teaching Project Management and Total Quality Management at the University Rovira i Virgili of Tarragona for the last five years. He received his BSCh and PhD degrees from the University of Barcelona and his MBA fron ESADE. He is currently an assessor for the European Quality Award and practices as a consultant in TQM. His research interests include the application of TQM principles in the teaching and learning processes and the modeling of organizations.*

mum of four students from a total of forty candidates in 1983. This situation could have ultimately led to the elimination of the ICh option. The faculty then decided to focus attention on the undergraduate program and to adopt a holistic and professional approach to education. It is worth noting that none of the nine faculty members involved in this decision was yet a full professor in 1983 and that seven of these positions were temporary Assistant Professorships, heavily dependent on teaching needs. Thus, the motivation to change learning strategies and course development was high.

The first faculty decision was to abandon traditional lecturing so that different learning and teaching styles[7-10] could be implemented in the third-year course. In particular, the strategies and actions that were field tested had the following characteristics:

- *Cooperative learning[11] was introduced because students learn more by doing things than by simply hearing or seeing.[9]*
- *Professors were free to experiment and evaluate different learning strategies, with colleagues and students providing direct feedback.*
- *Contents and the corresponding classwork were structured as a set of activities carried out cooperatively by students[12,13] during three hour-long sessions.*
- *Students decided the objectives of each class session within the framework of the syllabus of the course. In other words, they decided what to do next and how to do it.*
- *Students developed a final design project during the second semester of the course.*
- *A strategy of continuous evaluation, including self-assessment, was introduced in some activities to enhance students' involvement in the class sessions.*

The purpose of [this] paper is to analyze the key factors in achieving involvement and active participation of faculty in the conception and implementation of new and effective teaching strategies.

Implementation of the above characteristics into the "Fundamentals of Chemical Engineering" course favored the adoption of metacognitive learning strategies.[14-17] For example, students had to comprehend the demands of a given task and to respond to them during development of the different classroom activities. Students were responsible for their own learning and learned how to learn, *i.e,* they recognized and controlled the learning opportunities and became aware of their own learning activities. This experience also helped them to develop other competencies such as creative thinking, work interdependence with personal accountability, individual responsibility, self-esteem, communication skills, and sharing the values of the organization. Students also developed the desire to learn continuously and to grow professionally in a multidisciplinary environment, not only in technical and scientific areas but also socially and in humanities.

The decision to adopt a student-centered educational model,[17] together with cooperation from students in this educational effort, had a remarkable impact on the student body as a whole. The percentage of students choosing the ICh option reached, and even surpassed, the levels before the enrollment crisis, finding a stable plateau around 75%. Another relevant effect was an increase in the performance of students while at the university and after graduation. Our graduates became the preferred choice of employers at the chemical and petrochemical sites located near Tarragona, and today, many of them occupy positions of responsibility in various world-class companies.

The third-year course also induced professors to experiment with different teaching strategies. Teaching the course jointly with more experienced professors became the training policy until 1993 when the new five-year undergraduate chemical engineering program was implemented. During the ten-year period from 1983 to 1993, seven professors out of the eleven that constituted the faculty participated in the initiative, and two-thirds of those actively involved in the initiative exported the model of cooperative learning to other courses taught in the last two years of the ICh option. Therefore, the prospects for continuous improvement of ChE education in Tarragona were excellent just before the new program started in 1993.

BACK TO TRADITIONAL EDUCATION

The New ChE Program • The new ChE Program generated high social expectations in Catalonia in 1993. This, together with the favorable evaluation of our ICh graduates by industry, conveyed a perception among faculty that everything related to academia would improve continuously, by itself, as a result of the previous momentum. The following factors were considered particularly relevant for the initial success of our new undergraduate offer and academic organization:

- *The design and deployment of a ChE undergraduate program attractive to students, employees, and the administration. The new studies were modeled after the most successful programs in North America and Europe, with input from world-class chemical companies and a reliance on our previous educational experiences.*
- *The segregation of a Department of Mechanical Engineering from the original Chemical Engineering Department, and the creation of a School of Chemical Engineering (ETSEQ) to provide the necessary visibility for the unique engineering educational project. A*

quality program was simultaneously launched to continuously improve the organization.

- *The hiring of young professors educated abroad and interested in excellence in research, undergraduate education, and transfer of technology to industry. The ChE department at Tarragona was the first in Spain to hire citizens from other European countries as professors.*
- *Transformation of the graduate school to offer an international doctoral program in chemical engineering.*
- *The assignment of the first-year engineering science courses to the most experienced professors, with the purpose of reproducing throughout the academic organization of the ETSEQ, the student-centered approach to ChE education achieved in the old ICh option.*

The design of the new program started in 1987, five years before the Spanish government established chemical engineering as a separate undergraduate program and degree. A semester organization was adopted, with 55% of credits corresponding to regular classroom hours and the remaining 45% to laboratories, modeling and computer simulations, research and development projects, or internships in industry. The main characteristics are summarized in Table 1. Students learn physics, chemistry, mathematics, and engineering science during a first two-year cycle of undergraduate education and apply this fundamental knowledge to real problems, with emphasis on process downscaling. The objective of the third year is process upscaling because it is the core of engineering practice and technology development. The last two years bridge fundamental education with professional practice. This academic organization allows the adoption of Bloom's taxonomy of educational objectives.[18] Students advance from comprehension to analysis and synthesis of the essential scientific and engineering concepts in a smooth and continuous manner within each year of study and over the five years of the program.

The start of the new program in the fall of 1993 significantly increased the teaching load in chemical and mechanical engineering, and new faculty positions were opened to citizens of the European Union. Since that time, all new faculty positions have been advertised in international engineering journals. This new employment policy was later complemented with a continuing-education program aimed at all faculty. It consisted of seminars, courses, and workshops conducted by specialists from North America and Europe on topics such as learning strategies, cooperative learning, communication skills, project management, and quality in education. Most of these on-the-job training activities are also open to staff and to graduate students. Courses in Spanish and the Catalan language are also offered by the university to help new faculty.

Lessons To Be Learned • The above undergraduate ChE program features the most widespread methods of learning activities applied in chemical engineering education, with project-oriented capstone courses, short stays in university research laboratories, and industrial placement. Nevertheless, the first evaluation carried out in 1995, two years after the start of the new program, showed student retention of only 60%, lower than expected. In addition, most teaching had reverted to lecturing.

The return to traditional lecturing by both new faculty and the professors who had previously experienced cooperative learning was taken very seriously by the heads of the two departments involved because the success of cooperative learning and of any other innovative educational method can be fully attained only when they are applied continuously and systematically in an undergraduate program. We cannot expect to move from the professor-directed and professor-centered model of education toward student-centered instruction[7] just by endowing a few scattered courses with active learning. An undergraduate chemical engineering program should offer individual students the possibility of experiencing their own approaches to learning, to develop engineering and cognitive skills, and thus to become fully accountable for, and have ownership in, all organizational processes that are relevant to corporate life or to commercial organizations.[5,6] Moreover, deficiencies accumulated in such areas during undergraduate education are difficult to address after graduation by continuous on-the-job training, since corporations are reluctant to take unnecessary risks and dedicate resources to nonspecific training programs.

There are several factors that explain the return to traditional education at ETSEQ after the new program was implemented:

- *Faculty lost focus in education due to the extra effort*

TABLE 1
Summary of Contents, Present ChE Program

First and Second Years

Introduction to ChE and Process Downscaling
- Chemical Engineering and Physics (20%)
- Chemistry (9%)
- Mathematics (6%)
- Elective courses in science, mathematics and engineering (2.5%)
- Elective courses in arts and social sciences (2.5%)

Third and Fourth Years

Process Upscaling and Creative Management
- Chemical Engineering (25%)
- Elective courses in science, mathematics, and engineering (10%)
- Elective courses in arts and social sciences (5%)

Fifth Year

Professional Practice and Internship in Industry
- Internship in industry, R&D, and final project (15%)
- Elective courses in science and engineering (2.5%)
- Elective courses in arts and social sciences (2.5%)

required by implementation.

- *The student/faculty ratio increased without augmenting the population of candidates and the standard of selected students. Under these circumstances there is a natural tendency to do whatever is more usual and easier, which in education means lecturing.*
- *The success inherent to implementation of the new program could have contributed to the perception among faculty that there was no further need to procure social recognition and support.*
- *The shift of faculty interests toward research instead of excellence in education, caused by a governmental promotion policy based solely on research productivity.*
- *The tremendous increase in the number of professors in chemical and mechanical engineering, together with the incorporation of professors from other departments to teach mathematics, chemistry, economics, and computer science, made coordinating and sharing experiences more difficult. Also, it was hard to maintain the notion that faculty must act as a team*[19] *and service the department through education and research, much as we expect our students to work and cooperate efficiently in teams.*
- *The incorporation of young professors with a different organizational culture was perceived as a loss of identity by some faculty, and a natural fear of change appeared in the organization. It should be noted that despite the interest of new faculty in education, they did not receive any training of effective teaching until 1996.*

Nevertheless, consideration and discussion among faculty of all these factors was not sufficient to adopt corrective actions and to substitute a significant percentage of lecturing with other more efficient teaching strategies in 1995. As a consequence, the former holistic approach of ChE education experienced in the ICh option[12,13] was re-examined to identify the key elements that made this previous organization successful and sustainable. Then new elements were considered in view of the situation created by the new program, and finally, corrective actions were taken. The following section presents these analyses and the corrective actions, in addition to the results obtained.

A SUSTAINABLE AND INNOVATIVE SYSTEM

Key Elements • The above considerations led to the following synthesis of key elements to sustain cooperative learning and faculty involvement:

- *The holistic approach adopted in the old ICh option was a shared learning opportunity for both students and professors, with everyone assuming responsibilities.*
- *Professors experienced different learning strategies and became confident about effective teaching.*
- *Students felt they were a part of the organization and of the decision-making process, with the only limitations being imposed by the syllabus of the course.*
- *Professor and students alike were actively and personally involved in all classroom activities.*

In fact, these factors implied incorporation of the Kolb learning cycle[9] into the professor's training process, in a learning-to-learn hands-on classroom experience. The professors involved in the old ICh option were capable of generating new concepts from observing the students working in teams as they advanced in the series of classroom activities that constituted the course. From this new evidence, both professors and students created additional actions and learning experiences. Thus, the learning cycle advanced naturally in the course and improved the metacognitive skills to learning[14-17] of all involved. Also, a deep approach to learning[9] was favored. The experimental character of the course, blended by the holistic approach to engineering education, and a decision-making process shared by professors and students constituted the core of the above four key elements.

Once the key factors of the previous experience had been identified, the question was how to implement cooperative learning and the holistic approach in the new program. How could lectures and classroom activities scattered over several one-semester courses taught by senior and junior staff from different departments be integrated into one single educational effort? How could we reintroduce the Kolb learning cycle into the classroom so that professors and students become confident in their everyday learning-to-learn experience? How could faculty recover the motivation to act as a team interested in both education and research?

Holistic Approach Within the Academic Organization • Two fundamental actions were taken during the academic years of 1995 through 1998 to reintroduce the holistic approach to student-centered engineering education[12,13] and to recover the sense of teamwork among faculty. One-semester design projects, carried out by teams of first-year students led by junior or senior students, were introduced, and a continuous-improvement quality program was begun. In what follows, only the introduction of the design projects is presented and discussed.

The first-year design project had the following objectives:

- *To redeploy cooperative learning in the organization as a whole.*
- *To enhance students' responsibilities in the decision-making processes.*
- *To include open-ended problems where professors do not have the only solution.*
- *To integrate knowledge; students should be immersed*

in a multidisciplinary and humanistic educational environment.

- *To use faculty as a team; professors should be encouraged to cooperate and innovate.*
- *To enhance junior and/or senior students' role in the educational organization; students should learn to lead a project, to share the culture of the organization, and to perform professional tasks while at the university.*
- *To teach ChE students to think and to work as engineers and to use the highest cognitive levels of Bloom's taxonomy from the beginning of their education.*
- *To use it as a test for evolution toward a new organization of the curriculum in Tarragona; the test should lead to a student-centered, sustainable educational system.*
- *To foster synergetic learning and metacognition where students help other students to learn; junior and/or senior students also learn when coaching first-year students.*

From an organization point of view, execution of the project required severing class hours from the participating courses so the total teaching load per semester was not increased. The scope of the project had to be concrete, but open enough to allow the eventual integration of almost all subjects and to secure the interest of the professors. Three trials were carried out during the second semester of the first year over the period from 1995 to 1998. Table 2 summarizes the academic organization under which these trials were executed.

The first project dealt with the design of a craft oven and integrated only the first-year courses of transport phenomena and fluid mechanics (see Table 3). These projects were directed by third-years students as part of their work in the unit operations laboratory. The second trial integrated the transport phenomena laboratory course with teams of first-years students led by fourth-year students enrolled in project management and management practice courses. The project dealt with the catalytic conversion of the lactose contained in a water effluent from a dairy factory into glucose and galactose. The teams presented their results during two poster sessions at the end of the semester. The third test involved four first-year courses, with the addition of numerical methods, and two fourth-year courses, as shown in Table 2. A total of 145 first-year students, organized into groups of five, were directed by 29 fourth-year students to develop the preliminary design of a low-density polyethylene plant.

The third trial received good evaluations from all. Also, faculty members were asked to participate in the poster presentations to get acquainted with the new project system. As a result, the implementation scheduled for 1998-99 will cover a total of 13 courses and 16 faculty members (see Tables 2 and 3). Three hours per week will correspond to face-to-face teamwork of first- and fourth-year students in the classroom. During the remaining hours assigned to the project, first-year students will work on their own but with access to the professors for consultation.

TABLE 2
Summary of Student-Directed Design Projects

	First Trial	Second Trial	Third Trial	Implementation
topic	Craft oven	Lactose Recovery Plant	Polyethylene Reactor	Industrial Waste Treatment Plant
class hours/week	1	2	4	6
% of project in first year	20	40	50	50
coach	3rd-yr student	4th-yr student	4th-yr student	4th-yr student
subjects involved in first year	2	3	4	8
subjects involved in fourth year	1*	2	2	5
professors involved	3	5	8	16
teams	21	23	29	35
students/team	5-6	5-6	5	4

* *Third-year subject*

TABLE 3
First- and Fourth-Year Subjects in Current Program (Hours/Week)

First year - First semester	First year - Second semester	Fourth year - First semester	Fourth year - Second semester
Algebra - 3	**Statistics -3**	**Process Manufact. & Control Lab - 8**	**Chemical Process Design - 4**
Calculus - 6	**Transport Phenomena - 4 (2+2*)**	**Electives - 8**	**Economy & Industrial Organization - 4**
Physics - 6 (4+2*)	**Fluid Mechanics - 4 (2+2*)**	**Project Management - 4 (2+2*)**	**Project Management Practice II - 4 (1+3†)***
Chem. Eng. Funds. - 4 (2+2*)	**Transport Phenomena Lab - 7 (6+1*)**	**Project Management Practice I - 4(1+3†)***	**Environmental Technology - 4 (2+2*)**
Physical Chemistry - 4 (3+1*)	**Numerical Methods - 3 (2+1*)**	**Convective Heat/Mass Transfer - 4 (2+2*)**	**Electives - 12**
Inorganic Chemistry - 4 (3+1*)	**Analytical Chemistry - 4**		

* *hours/week assigned to design project*
† *hours/week of face-to-face teamwork*

The progression experienced in the degree of professors' involvement has encouraged ETSEQ to test the same organization in the second year of undergraduate education. This trial will be carried out with the participation of 7 subjects and 6 professors. The second-year preliminary design project will emphasize process downscaling and will be organized around the two-semester chemical engineering laboratory.

A direct benefit from the experience is that we have reproduced, on a larger scale, the model of education that was successful in the old ICh option. Professors become sponsors of cooperative learning and perform as consultants, and their curiosity is enhanced because they are faced with real and interesting problems. As a consequence, we are involving professors to a higher degree than before, and students are learning what chemical engineering is all about from the first year of their undergraduate education. From an educational point of view, the project experience is a good example of learning synergism; first- and fourth-year students cooperate in their own instruction and are learning together. First-year students (with the help of fourth-year students) act as team leaders and coaches, apply knowledge to a real problem, develop their competency and skill, and learn how to learn and how to cooperate with peers. Fourth-year students integrate into the academic organization by assuming specific responsibilities and by acting as project managers. They reinforce their own learning-to-learn strategies when confronted with a teaching responsibility beyond simple tutoring experiences. The opportunity to re-examine fundamental subjects or topics, to define strategies to help first-year students overcome their learning difficulties, and to manage a real project until completion are also invaluable professional assets related to team management and organizational behavior.

CONCLUDING REMARKS

Altogether, our experience indicates that professors have a natural tendency to teach by lecturing since that is how they were taught. The yearly design projects compel professors, otherwise isolated in teaching their courses, to cooperate with other faculty and with students. This new holistic approach represents a benchmark where professors can continuously experience effective teaching and innovation in education. The strategies have also contributed to their personal and professional development.

The current study shows the benefits of incorporating student-centered learning into classroom instruction, the difficulties of doing so, and the ease of reverting to more traditional and less effective approaches when emphasis on effective teaching is relaxed. Also, it is shown that the holistic approach, with first-year students working in projects led by junior or senior students, can be easily extended to full-scale curriculum improvement throughout an academic organization. The outburst of creativity and participation that was attained fifteen years ago at Tarragona has been revived.

ACKNOWLEDGMENTS

This paper was made possible through the collaboration of students and the support received from the School of Chemical Engineering, in particular from its Director, Professor Francesc Castells. The authors would also like to acknowledge the involvement of Professors J. Bonet, I. Cuesta, A. Fabregat, J. Font, C. Garcia, A. Garijo, R.M. Gilabert, J. Grifoll, A. Mackie, F. Medina, D. Montané, J. Renau, J. Sueiras, and L. Vega in the implementation of the first- and second-year projects. Their encouragement and suggestions have been an invaluable asset during the trial process of the first-year projects.

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COMPUTER-MEDIATED, COLLABORATIVE LEARNING IN CHE

At the University of Ottawa

DAVID G. TAYLOR
University of Ottawa • Ottawa, Ontario, Canada K1N 6N5

The undergraduate chemical engineering curriculum at the University of Ottawa includes an introductory course in process dynamics and control. Taught to third-year students during their winter semester, it consists of three hours of lectures per week. A typical class has twenty-five students.

As part of a University initiative to incorporate computer technology in the classroom, I received a grant to develop a computer-based version of this course. Using this funding, an undergraduate student from our co-op program, Alain Turenne, and I constructed a series of computer-based modules and interactive simulators to allow independent study of the course material.

With the core material now available in a self-paced, computer-mediated format, I was able to rethink how I managed the lecture hours. I had from time to time incorporated collaborative, in-class problem solving sessions in my lectures, whereby students worked together in small groups to solve problems related to that day's topic. I decided to make this student-driven activity the focus of all of the lecture periods. This paper describes how I combined computer-assisted learning with collaborative learning in this course and presents both students' and instructor's impressions regarding the effectiveness of the approach.

COMPUTER-MEDIATED LEARNING COMPONENT

The computer-mediated portion of the course consisted of a series of nine modules. The material for the modules (Table 1) was drawn largely from Thomas Marlin's text,[1] with additional material taken from other standard textbooks in the field.[2-4] Each module provided a condensed review of its topic, although it included more detail than one might expect from lecture notes alone.

The modules employed interactive text, graphics, and animation to present the core material of the course. We built these using Asymetrix, Inc.,'s authoring software, Multimedia Toolbook. Toolbook provides a powerful, object-based graphical framework for producing computer-based training software for Microsoft operating systems (Windows 3.x, Windows 95, and Windows NT 4). Beginning with an empty window, we added various components (such as buttons, text fields, images, animation, etc.) to create a page within the module. These components were then scripted to respond to keyboard and mouse events (such as button clicks), imparting to the page its interactive qualities (see Figure 1). Finally, the nine course modules were linked through a graphical menu (see Figure 2).

To supplement the Toolbook modules, we constructed four dynamic simulators that students later used to explore the effects of process-model parameters and controller-tuning parameters on system dynamics. We built these using Delphi, an object-oriented, visual programming language based on Pascal and produced by Inprise (formerly Borland) Corporation. The Delphi development environment is similar to that of Toolbook; programmers add visual components to empty windows and then write the requisite code for these components as well as for the numerical routines. The final simulators included a graphical user interface through which students could adjust model parameters and view plots of the process response (see Figure 3). Further, students could run these simulators directly from the modules.

We designed and constructed the modules and simulators over a one-year period prior to introducing them into the course, after which time we installed them on a PC network

An Associate Professor of Chemical Engineering at the University of Ottawa, David Taylor received his BASc in Engineering Science at the University of Toronto and his PhD in Chemical Engineering from the University of British Columbia. His research focuses on tissue engineering, process modeling, and computer simulation. He is also keenly interested in distributed and computer-mediated learning.

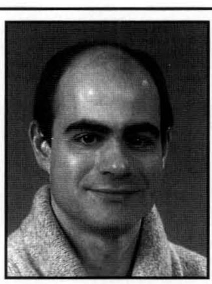

TABLE 1
Module Content

Module	Contents
1. Introduction to Process Control	• definitions • principal control components • feedback vs. feedforward control • calculating control benefits
2. Mechanistic Modeling	• modeling methodologies • defining a modeling approach • developing the model
3. Empirical Modeling	• motivation for empirical modeling • procedural approach to empirical modeling • statistical model building
4. Analyzing Process Dynamics	• dynamics of linear lst- and 2nd-order systems • SISO and MIMO systems • Laplace domain for linear systems • transfer functions and block diagrams • frequency domain for linear systems
5. The Feedback Control Loop	• the feedback loop • process elements and instrumentation • block diagrams revisited • control performance measures
6. PID Controllers	• the feedback loop revisited • proportional mode • integral mode • derivative mode • PID control
7. Stability Analysis	• stability and process control • stability criterion • Routh analysis • direct substitution method • frequency response analysis
8. Tuning PID Controllers	• considerations and criteria for tuning • Ciancone correlations • Ziegler-Nichols correlations • issues of fine tuning
9. Digital Control and Filtering	• digital feedback control algorithms • signal filtering • valve control and failure modes

located in the engineering building at the University of Ottawa. The classroom housing these PCs was designated a "quiet room" so that the students could study the modules at their convenience. In addition, I constructed a course web site from which the students could download the modules to run from home. The site also contained supplementary course material and a Java applet for retrieving marks on-line.

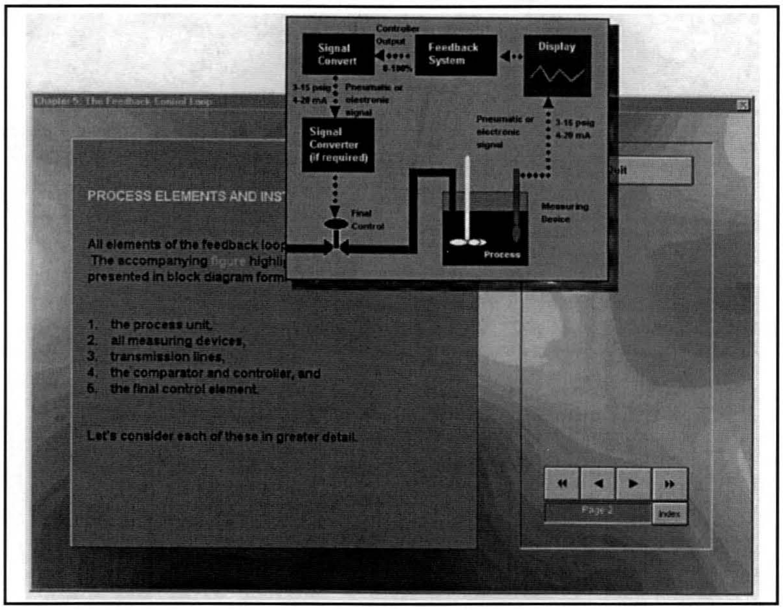

Figure 1. A screen capture of a page from one of the course modules. The pop-up box is animated.

COLLABORATIVE LEARNING COMPONENT

A typical single semester course in chemical engineering at the University of Ottawa consists of three lecture hours per week; these are normally delivered in two ninety-minute sessions. In the process control course, however, I combined the two weekly lectures into a single, three-hour session. While one would expect a lecture of this length to tax even those with ironclad concentration, it proved well suited to the collaborative, problem-based sessions used in this course.

Each week the students were given an assignment that was due two days before the next lecture. In addition, they were assigned a module (or portion thereof) to review for the following week. Each student was asked to submit, together with his/her assignment, a review sheet that highlighted any confusion with the subject matter contained in that week's module. The review sheet also contained space for the student to provide feedback re-

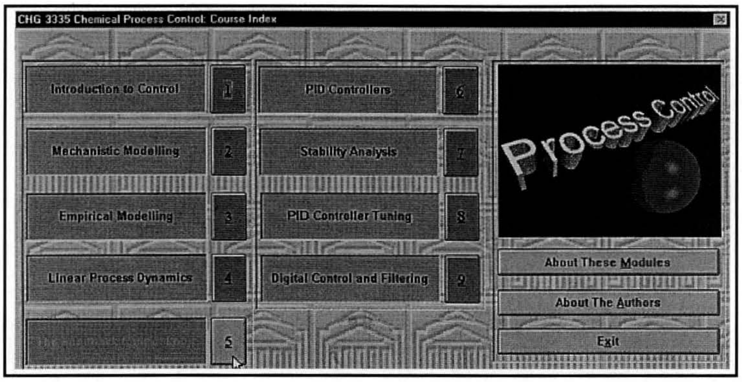

Figure 2. A screen capture of the modules' menu window.

garding the design of the module.

Prior to each weekly session, I would look over the review sheets, noting the areas of concern raised by the students. I would then design a set of short questions (normally requiring no more than fifteen minutes to complete) and a brief fifteen-minute lecture that focused on the current module's content and addressed those problem areas identified by the students.

The three-hour session would start with the prepared lecture, after which time students would move into small groups. (These groups were formed at the beginning of the term.) Each group would be assigned the same in-class problem and given a short period of time to work on it. During this time I would move through the class and provide limited guidance where needed. I would then randomly select one group from the class to present its solution to the problem. While no mark was given for "right" answers, the group was evaluated on its understanding of the problem and its ability to formulate a solution method. In this way the group presentation served as a springboard for class discussion regarding the problem and its solution. A typical three-hour lecture would include several of these exercises.

ASSESSMENT

The Students' Perspective

Since the standard course evaluations issued by the University of Ottawa do not directly address matters concerning course delivery modes, I undertook my own student evaluation approximately half-way through the term. Assessing the students' reaction to the new teaching style at this stage in the course also permitted me time to make any changes that seemed necessary from the students' perspective.

In addition to the standard questions appearing on the University of Ottawa's form, the evaluation included three questions relating to the new teaching style. The first of these read

> *Compared to other lecture styles that I have experienced I find the approach in this class to be..."*

and offered five choices from excellent to very poor for the student designation. The second question was

> *I find the time spent on in-class problem solving to be...*

with choices of "Very Helpful" to "A Total Waste" on a scale of five. The final question

> *I find the computer-based modules as learning aids . . .*

offered the same five choices listed under the first question.

The thirty anonymous responses to these three questions are presented in Figures 4a, b, and c, respectively. Overall, the students preferred this form of lecture to the standard, passive approach. As the responses to question 2 demonstrate, students particularly enjoyed the opportunity to apply their problem-solving skills in a structured, professor-mediated format. At least one student also saw value in having to present a solution to the rest of the class, as (s)he noted in the following comment:

> *Although I do not particularly like speaking in front of the class, I find presenting assignments and in-class problems useful. It forces me to keep up with the course material so that I know what I'm talking about when presenting.*

Of course, not all students saw it the same way. Another said

> *I think in-class teaching should be more emphasized since it benefits the whole class, rather than in-class problems which*

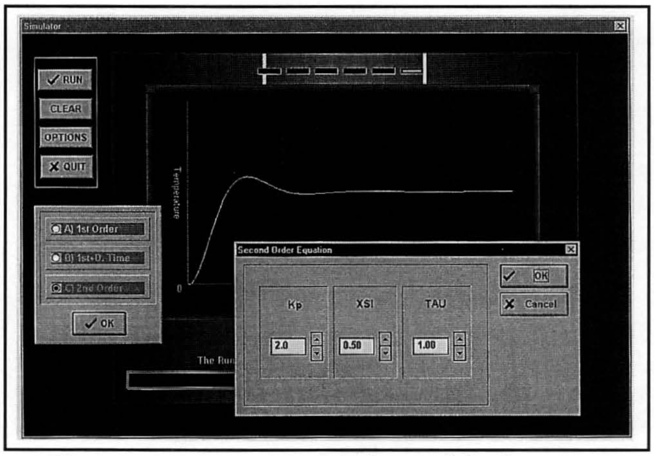

Figure 3. *A screen capture of one of the dynamics simulators accompanying the course modules.*

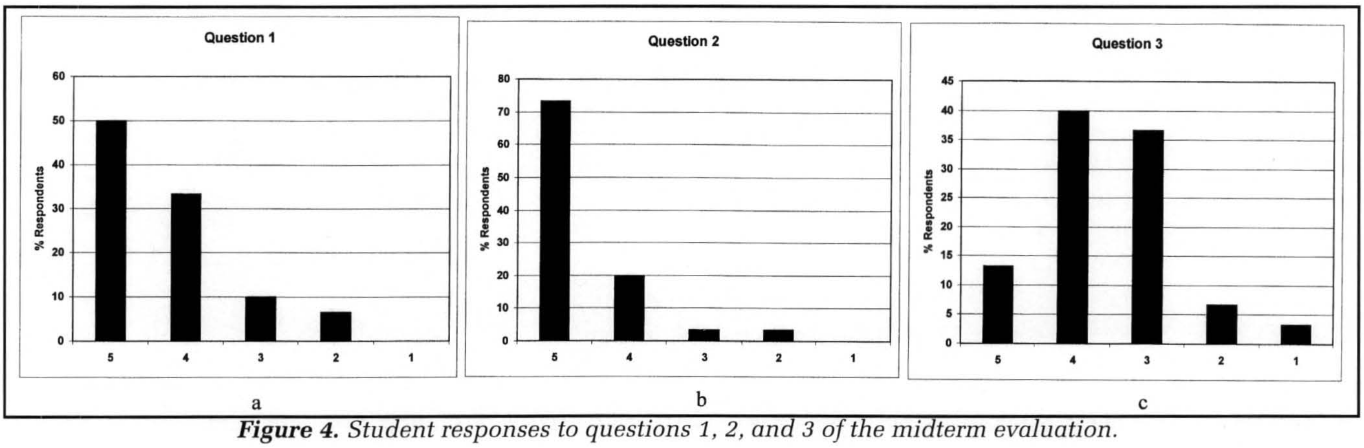

Figure 4. *Student responses to questions 1, 2, and 3 of the midterm evaluation.*

usually benefit the group doing the problem.

(I found this remark puzzling, since all groups were required to complete each question and since no group knew ahead of time who would be presenting the solution to the class.)

The overall response to question 3, though favorable, suggests that students were somewhat less enthusiastic about having to review the modules each week. The weekly feedback regarding the modules' structure and content was generally positive, leaving me to suspect that some students simply objected to having to spend time reviewing them outside of class. (It is worth noting that the average module would require less than three hours to complete, implying under 2.5 review hours per week for the course.) Further, since they could not print out the modules' content directly, students had to generate their own course notes. Not surprising, several students stated on the evaluation sheet that they would have preferred the option to print out the module content. But this limitation was deliberate, since I felt that the note-taking was valuable from a pedagogical perspective.

The Professor's Perspective

Admittedly, the combined collaborative, computer-mediated learning methodology used here required more work outside of the classroom: customizing each weekly session to address student comments, maintaining the course web site, and updating the course modules. But I did not find that any of these tasks required an inordinate amount of time.

The most significant changes for me as instructor lay in the classroom. First, the class became student-centered rather than professor-centered. This altered my role significantly from one of lecturer to one of facilitator—it also raised the students' level of interest during the lecture. The students seemed to quickly adapt to their new, and more prominent, role; in fact, the overall mood in the classroom was very positive. (It is worth noting that none of the students complained about the length of the weekly sessions, even though these sessions were twice as long as the standard lecture.) Attendance was also exceptionally good. Whether this was due to increased interest among the students in the course, or due to the fact that students were graded on their participation in the problem sessions, or attributable in varying degrees to both, is unknown. But the atmosphere within the class was significantly better, compared to other courses that I have taught using a more formal lecturing approach. Students in this class were far more inquisitive, eager to ask questions relating not only to the in-class problems, but to broader issues of process control. They were also far less hesitant to seek clarification during the lecture.

Clearly, this form of collaborative learning does not need to be supplemented with computer-based learning. The value of the modules, to my thinking, lay with their ability to present the conventional course material more effectively than paper handouts. In particular:

1. Being interactive, the modules engaged the students in the learning process (this is particularly true of the simulators, which allowed the students considerable freedom to explore the causal relationships in feedback control loops).
2. They allowed students to process information in a nonlinear, and consequently more flexible, fashion. For example, hyperlinks in the modules give students the choice of either delving further into a topic or continuing to the next one, without compromising the flow of the overall presentation.
3. They integrated several media forms (text, graphics, and animation) to present the subject matter, thereby offering various perspectives on the same topic.

The modules therefore provided added incentive for students to review the material ahead of time, which in turn contributed to the success of the classroom sessions.

CONCLUDING REMARKS

Collaborative learning is well established as an effective method for teaching engineering students. For example, Felder included in-class, small-group problem solving as part of a longitudinal study of student learning styles.[5] In that paper, he notes that students' evaluations were "consistently and overwhelmingly positive" and that their performance was significantly better. Of course, Felder's study incorporated cooperative learning, which goes well beyond the small group sessions employed here. But improved student attitudes that he observed are consistent with this study as well.

Finally, the teaching technique applied here requires that students undertake more independent study than might be expected with conventional lecturing. Computer-mediated delivery of the course material provides an attractive alternative to notes in this case, offering new approaches for students to assimilate both theoretical concepts and their ramifications in practical engineering problems.

ACKNOWLEDGMENTS

The author wishes to acknowledge Mr. Alain Turenne, whose work during the design and construction of the computer-based modules is greatly appreciated. The development of these modules was made possible through a grant from the University of Ottawa.

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A SOFTWARE PACKAGE FOR CAPITAL COST ESTIMATION

P.T. VASUDEVAN, DEEPAK AGRAWAL
University of New Hampshire • Durham, NH 03824

EconExpert is a software package for capital cost estimation, primarily intended for use by chemical engineering students in plant design, and can be run on any Unix platform. The system prompts the user for various input, such as equipment category, equipment type, equipment sub-type, material of construction, and operating pressure, and then calculates the bare module cost of the equipment. EconExpert is also programmed to calculate the grass-roots capital if the user enters information on all relevant equipment in a plant. It also provides the user with help.

IMPLEMENTATION OF ECONEXPERT

EconExpert is an interactive software package for capital cost estimation. The system was developed in CParaOPS5 and uses 'C' external functions. It uses cost data from *A Guide to Chemical Engineering Process Design and Economics*[1] and is thus a useful supplement to the text. The cost data in the text are expressed graphically in the form of charts, and according to the author, "the charts are accurate enough for preliminary design estimates and are certainly adequate for classroom work." In this software package, the plots are represented as polynomial equations, and these equations are stored as 'C' functions. If the purchase cost is a function of more than one variable, a multiple regression technique is used to fit the data. The output from the routine results in a polynomial equation that gives the closest fit to the data.

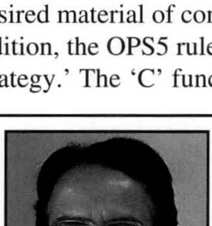
OPS5, developed at Carnegie Mellon University in 1978 by Charles Forgy,[2] is a language especially developed for rule-based expert systems. CParaOPS5 is a parallel version of OPS5, written in 'C' programming language. One advantage of CParaOPS5 is that it has parallel processing capabilities in addition to the ability to run on a uniprocessor machine. It also allows the user to write external functions in 'C' language, which is an added advantage for calculation-intensive applications since OPS5 is not good in mathematical computing. Another advantage is portability of the program. CParaOPS5 converts the OPS5 program to 'C' language, and this 'C' language program can be compiled on any 'C' compiler without needing CParaOPS5.

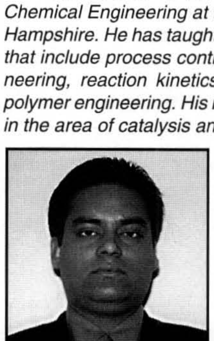
In addition to the above capabilities, another important feature of CParaOPS5 is that it allows the database to be included in a separate file. The advantage is that the database can be accessed and modified by the user at any time. CParaOPS5 also allows the input to be read from a file and the output to be written to files, which makes it easier for the user to supply data and to obtain results.

THE SYSTEM STRUCTURE

The system consists of a user interface and an extensive knowledge base. This knowledge is represented in OPS5 rules and 'C' external functions. The OPS5 rules mainly ascertain the type of equipment and desired material of construction, and also provide help. In addition, the OPS5 rules contain information on the 'control strategy.' The 'C' func-

P.T. Vasudevan *is Associate Professor of Chemical Engineering at the University of New Hampshire. He has taught a number of courses that include process control, biochemical engineering, reaction kinetics, mass transfer and polymer engineering. His research interests are in the area of catalysis and biocatalysis.*





Deepak Agrawal *graduated with a MS degree in Chemical Engineering from the University of New Hampshire in the area of Expert Systems. He is a management consultant helping leading global companies with strategic and tactical issues in the areas of supply chain, operations, and product development.*

tions contain information on cost estimation, information on the minimum and maximum sizes available, and information on other key factors.

The system consists of several levels. At the upper level, basic information is sought from the user. After it is supplied, the system moves to the next level to gather more detail information. The levels are

Start	*Starts execution of the program and asks about cost index*
Level I	*Asks about equipment category*
Level II	*Asks about equipment type*
Level III	*Asks about equipment sub-type and calculates purchase costs*
Level IV	*Asks about material of construction and other information, calculates various factors, and uses these factors to calculate bare module factor and bare module cost*
Final Level	*Adds bare module cost of the equipment to the total bare module cost, asks if the user wants to cost one more equipment. If "yes," then goes to Level I—otherwise calculates total capital cost and ends the session.*

The system prompts the user for various input, such as equipment category, equipment type, equipment sub-type, material of construction, and operating pressure, and then calculates the bare module cost of the equipment. EconExpert is also programmed to calculate the grass-roots capital if the user enters information on all relevant equipment in a plant.

The structure of the software package is described more fully in the following sections.

■ *Start*

Once the program is started, it prints a welcome message, initializes the variables, and asks for the cost index. After the cost index is supplied, the information is stored for the duration of the session, avoiding the need to seek this information while costing several pieces of equipment.

The cost index is asked by the rule "ask-cost-index," which in turn calls an external 'C' function. This function asks for the cost index, accepts the input, and returns the value to an OPS5 rule.

■ *Level I*

In this level, the user is prompted to choose the equipment category of interest to the user. There are 18 broad categories of equipment such as heat exchangers, pumps, mixers, etc. When the user supplies the desired information, the system checks the answer and transfers control to the next level. The validity of the input is checked by another rule, and if the answer is valid, the system moves to the next level in the hierarchy. If the answer is invalid, the system prompts the user again for a different input.

■ *Level II*

After the equipment has been selected, the system moves to this level to obtain additional information. There is one rule for every category, and each rule contains information on the type of equipment. For example, under "mixers" there are several types available. The system needs to ascertain the user's interests and hence it asks about the desired "type." When the system receives the input, it validates it by using rules written for checking invalid inputs. These rules are written in such a way that they can be shared by various categories. After the system gets the correct information, it goes to the next level to seek additional input from the user.

■ *Level III*

After the system receives input on the type of equipment, it queries the user about the "sub-type" desired. For example, sub-type could be items such as "stuffing box" or "mechanical seal." When this information is obtained, it requests further information relating to that particular equipment, such as size, area, etc., in order to calculate the purchase cost. This is done by an external function written in 'C.' This function has information on the minimum and maximum sizes available for the equipment. If the size specified by the user is less than the minimum size available, it increases the size to the minimum size; if the specified size is larger than the available maximum size, EconExpert splits the unit into smaller equal-sized units. This is a simplistic approach, but this rule can be easily changed as more knowledge becomes available. The relationship between purchase cost and size is expressed in the form of equations, using 'C' functions. After the functions calculate the purchase cost, the system moves to the next level.

Certain types of equipment do not possess a "sub-type." In these cases, the tasks of Levels II and III are combined; that is, after determining the type of equipment, the system directly proceeds to the cost-calculation step.

■ *Level IV*

The cost of a piece of equipment depends on the construction material. There are factors that take into account the effect of construction material on the equipment cost. In this level, the system asks the user for a preferred material of construction and then calculates the appropriate factor. This level also has information for validating the input.

In some cases, the cost of equipment varies depending on the operating pressure. This is taken into consideration by employing a "pressure factor." Additionally, the system has information on several other factors such as superheat, corrosion, etc. These factors are also calculated in this level. When the system has determined all these factors, the purchase cost is multiplied by an overall factor, obtained by multiplying all the relevant factors, to give the bare module cost. After the system has calculated the bare module cost of the equipment, it moves to the last level.

■ *Final Level*

In this level, the system keeps track of the total bare module cost of the plant by adding the total bare module cost of each piece of equipment. The system thus asks the user about costing new equipment, and if the answer is in the affirmative, the system goes to Level I again. If not, it calculates the total module cost of the plant and the grass roots capital. Once the system has calculated the grass roots capital of the plant, it prints the results and the session ends.

■ *Help Facility*

The system also provides help if requested. When the user prompts the system for help, it lists the different types of equipment available in a particular category. If the user asks for help in Level I, for instance, the system will print the list of available categories and will then prompt the user for input. The system provides appropriate help at each level and contains rules for transferring control between any level and the help facility, and vice versa. These rules are written in a way that can be shared by all categories.

SYSTEM TESTING AND USER REACTION

After development of EconExpert, the system's performance, reasoning, and knowledge were tested and validated. It was used by all seniors in the spring of 1998, and the bugs reported by them have all been corrected. The program was tested to check for the validity of its reasoning and also for its ease of use and aesthetic appeal.

We have used the software in other courses, such a biochemical engineering and thermodynamics. Thus, the software aids students not only in the senior capstone design class, but also in other courses where a quick economic evaluation of a chemical process plant or unit is required. The software has helped instructors in different courses to obtain relative-cost data. Students have found the program to be quite useful since it provides them with a quick means of determining the cost of equipment to obtain total capital cost, and in making economic evaluations of different processes or competing technologies.

The software is available on the University mainframe computers as well as Linux boxes, and students thus have ready access to it. Students have been uniform in their praise of the software since it is so simple to use and they can access it from anywhere in the University or from their homes. The software was used in the spring 1999 semester by seniors taking design and by juniors taking thermodynamics. Instead of spending an inordinate amount of time in obtaining cost data from the plots (which required careful interpolation, especially since the plots are rather small), the students are able to focus on the design problem itself and to quickly evaluate different flowsheets (technologies) or different options (equipment types) within a given process. Thus the pedagogical value of the package is quite high.

The system was tested by having users try it and noting their responses. EconExpert was tested for all the equipment it contains. The bare module cost supplied by the system is in agreement with values reported in the literature. The system is successfully carrying out all the tasks such as checking size, providing help, validating input, etc. The system also has the flexibility to be continuously updated as data become available in the future.

CONCLUSIONS

EconExpert is a software package for capital cost estimation. It is intended for use by students in chemical engineering and has a number of features, including

- *The movement of the system is efficient since it moves from a node at one level to a node at the next level, until it tracks down the right equipment. The way this system is written, it finds information about the equipment using very little computer time.*
- *It checks for the minimum and maximum sizes available. If the desired size is out of range, it knows what to do.*
- *It has a help facility to assist the user.*
- *It uses 'C' functions extensively since the design process is highly computational. The calculation part is encoded in 'C' functions to increase the efficiency of the system.*
- *The system has the capability of checking user input at every level.*
- *The executable code runs on any Unix platform. Readers may send e-mail to the author (ptv@cisunix.unh.edu) for more information about the software and its availability.*

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