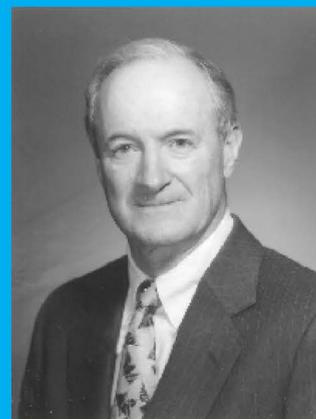




Joseph Reynolds

... of Manhattan College



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Polytechnic University

This one-page column will present practical teaching tips in sufficient detail that ChE educators can adopt the tip. The focus should be on the teaching method, not content. With no tables or figures the column should be approximately 450 words. If graphics are included, the length needs to be reduced. Tips that are too long will be edited to fit on one page. Please submit a Word file to Phil Wankat <wankat@ecn.purdue.edu>, subject: CEE Teaching Tip.

TEACHING TIP: ELEVATOR TALKS

PHIL WANKAT
Purdue University • West Lafayette, IN 47907

Both industry and ABET require that engineering graduates can communicate. Clearly the best way to achieve this is to have frequent assignments throughout the curriculum requiring writing and oral presentations. Unfortunately, oral presentations tend to require a significant amount of class time. An alternative oral presentation is the “elevator talk.” The scenario: a student steps into an elevator with someone she needs to persuade or sell. For example, the student may want to convince the person to hire her. She has from one to two minutes to do this.

I assigned the topic to the students (ask for a job), gave them the time (two minutes), gave them a copy of the scoring rubric (Table 1), and told them to prepare a talk that they will present extemporaneously, without visuals. There was no written assignment. In class, I assigned the “boss” for each person. Students were

told to assume that they knew the boss well enough to talk to. Presenters and bosses went to the front of the room and stood in the elevator. Talks were timed for a strict two minutes. Since two minutes is actually fairly long, most students finished early and had to do something—perhaps just stand there—for the remaining time. If they weren’t finished at two

minutes, the elevator door opened anyway and they had to summarize very quickly.

The students saw the relevance of elevator talks and were well prepared. Grading the talks with the scoring rubric was straightforward and I was able to finish the grading while the next pair walked to the front. Since it takes less than 30 seconds to change speakers, 20 two-minute talks can be done in a 50-minute period.

While not eliminating the need for more formal presentations,

elevator talks can provide an easy way to include oral communication in courses that normally would not have time. Grading all of the talks with the scoring rubric and then saving copies provides evidence for ABET that all students have been assessed and can do oral presenta-

Attribute	Not Acceptable	Barely Acceptable	Meets Expectations	Exceeds Expectations
Logical topic order	Disjointed; no organization	Parts out of order	Organized by guidelines	Superior; enhances communication
Appropriate time use	Far too long or too short	Somewhat long or short	Appropriate length	
Objective	Not stated	Poorly stated	Clearly stated	
Background & Significance	Neither stated	Only one stated	Both stated	Both clearly stated
Conclusions	None	Present, but not logical	Logical & clearly stated	Logical & superior explanation
Presentation mechanics*	Many distractions	Some distractions	No distractions	Superior presentation
Response to questions (if any)	Not responsive	Incomplete	Clear and direct	Complete
Focus on person speaking to	Not focused; distracted, no eye contact	Some focus; some eye contact	Focused with good eye contact	Totally focused; excellent eye contact

* voice, poise, mannerisms

tions, at least at the barely acceptable level.

REFERENCES

- Mitchell, B.S., and V.J. Law, “Community-Based Presentations in the Unit Ops Laboratory,” Chem. Eng. Ed., 39(2), 160 (2003)

Author Guidelines for the LABORATORY Feature

The laboratory experience in chemical engineering education has long been an integral part of our curricula. CEE encourages the submission of manuscripts describing innovations in the laboratory ranging from large-scale unit operations experiments to demonstrations appropriate for the classroom. The following guidelines are offered to assist authors in the preparation of manuscripts that are informative to our readership. These are only suggestions, based on the comments of previous reviewers; authors should use their own judgment in presenting their experiences. A set of general guidelines and advice to the author can be found at our Web site: <<http://che.ufl.edu/~cee/>>.

- c Manuscripts should describe the results of original and laboratory-tested ideas. The ideas should be broadly applicable and described in sufficient detail to allow and motivate others to adapt the ideas to their own curricula. It is noted that the readership of CEE is largely faculty and instructors. Manuscripts must contain an abstract and often include an Introduction, Laboratory Description, Data Analysis, Summary of Experiences, Conclusions, and References.
 - An Introduction should establish the context of the laboratory experience (e.g., relation to curriculum, review of literature), state the learning objectives, and describe the rationale and approach.
 - The Laboratory Description section should describe the experiment in sufficient detail to allow the reader to judge the scope of effort required to implement a similar experiment on his or her campus. Schematic diagrams or photos, cost information, and references to previous publications and Web sites, etc., are usually of benefit. Issues related to safety should be addressed as well as any special operating procedures.
 - If appropriate, a Data Analysis section should be included that concisely describes the method of data analysis. Recognizing that the audience is primarily faculty, the description of the underlying theory should be referenced or brief. The purpose of this section is to communicate to the reader specific student-learning opportunities (e.g., treatment of reaction-rate data in a temperature range that includes two mechanisms).
 - The purpose of the Summary of Experiences section is to convey the results of laboratory or classroom testing. The section can enumerate, for example, best practices, pitfalls, student survey results, or anecdotal material.
 - A concise statement of the Conclusions (as opposed to a summary) of your experiences should be the last section of the paper prior to listing References.

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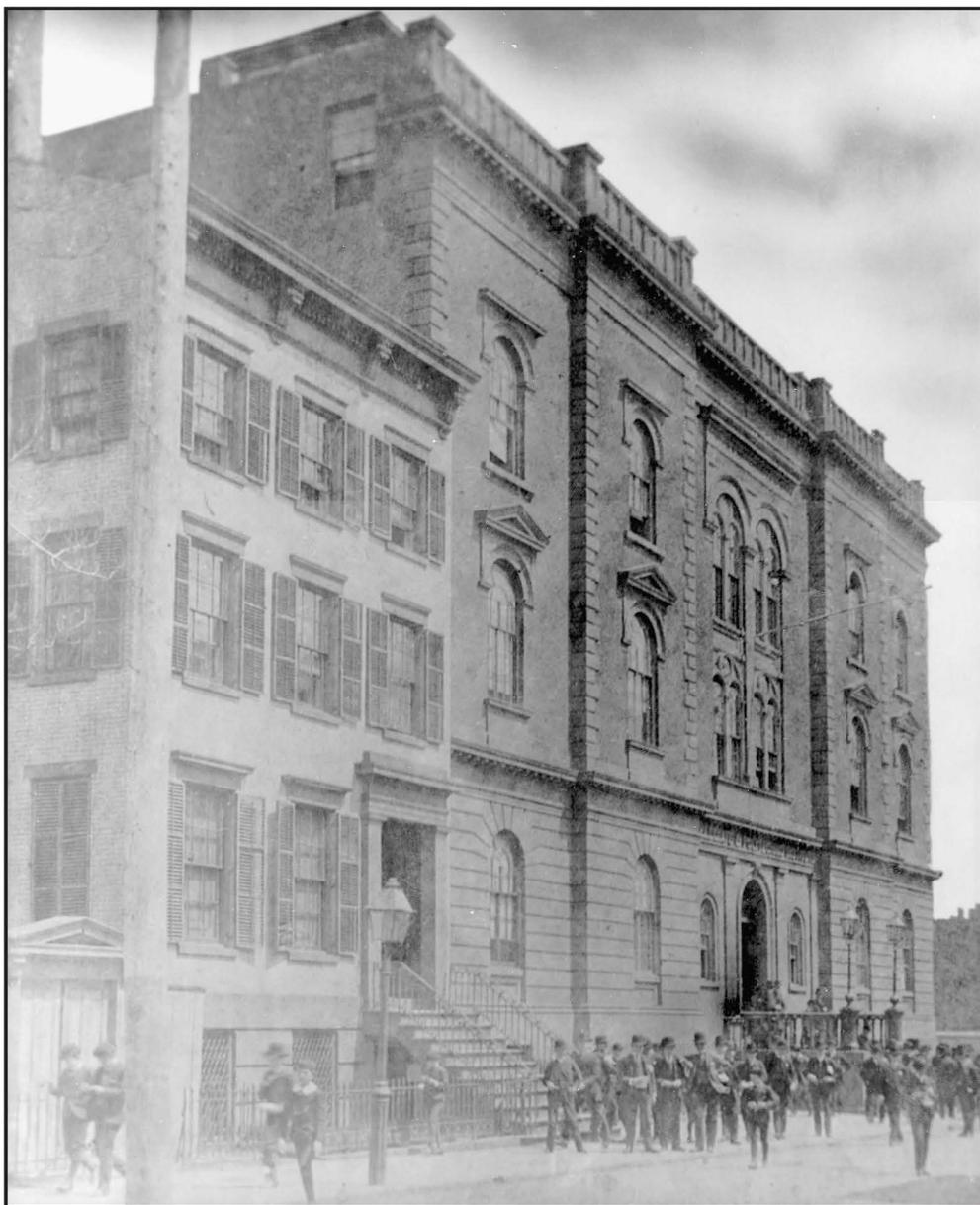
Chemical Engineering at Polytechnic University

EDWARD N. ZIEGLER
AND JOVAN MIJOVIC

The Brooklyn Collegiate and Polytechnic Institute was chartered in 1854, when the city of Brooklyn's rapidly growing population was 30,000 and Brooklyn was separate from New York City. This was roughly 30 years before the completion of the Brooklyn Bridge and prior to the Civil War. The stated purpose of the first Polytechnic Board was to establish "an educational institution in our midst, . . . to give our sons an education as would qualify them in a far higher degree, through an enlarged, liberal, and thorough training in a course of practical, scientific, and classical studies, to enter upon the active pursuits and duties of life," and "that its location should be as central, and as easily accessible as possible by public conveyance, from all parts of the city" In its earliest years, the college drew students from the mansions and substantial homes of the "Heights," the "Hill," the "Eastern District," and other parts of Brooklyn.

The Scientific Program leading to the Bachelor of Science degree was established for those bent in the direction of science and engineering, which in addition to theory included more than "200 laboratory experiments, field trips, and exercises." Between 1885 and 1890 the "Scientific" course of study was ultimately divided

into three areas of specialization: Engineering (Mechanical and Civil), Electrical Engineering, and Chemistry. The latter had offerings in applied and fundamental areas



A preserved picture of life at Polytechnic's main campus at the beginning of last century.

In 1898, Brooklyn became a part of New York City. Like Brooklyn, Polytechnic's services and influence have gone far beyond the borders of the Borough, through the university's worldwide contributions to science, engineering, and education. Polytechnic's modern Brooklyn site is still only two blocks from the Brooklyn Bridge, and all three of the city's major subway systems have stations within a few blocks of the Polytechnic, maintaining the spirit of its original charter.

Chemical engineering at Polytechnic University had its formal beginnings more than a century ago when the Department of Chemistry became the Department of Chemistry and Chemical Engineering at the Polytechnic Institute of Brooklyn, or PIB. **I.W. Fay** was the first head of the combined department in 1905, with only one chemical engineer on the staff—**John C. Olsen**. In those days, extensive use was made of eminent professionals in local industries as “consulting professors.”

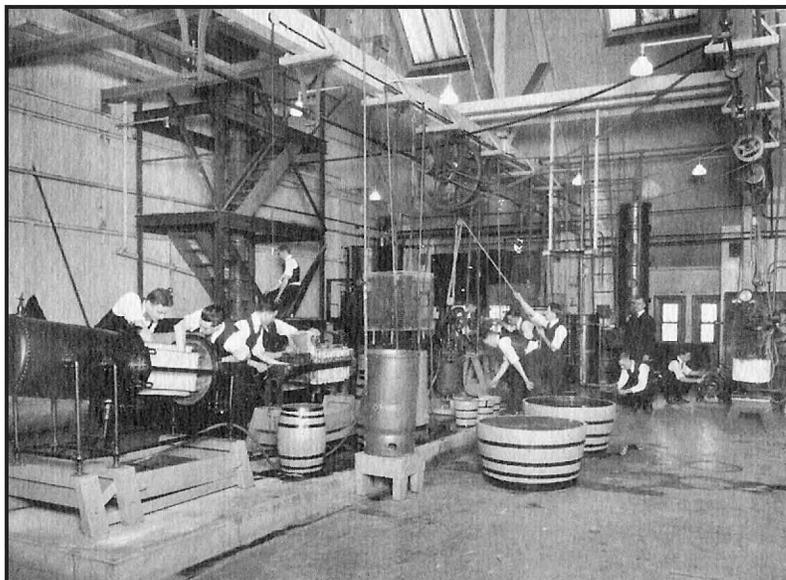
In 1925, the chemical engineering program at Polytechnic became one of the first engineering programs to receive accreditation by a national professional society, when the American Institute of Chemical Engineers (AIChE) listed it among the first 15 accredited curricula in chemical engineering. In 1931, a separate Department of Chemical Engineering was established, with Olsen as its first head. That same year Olsen was elected president of the AIChE, which he helped found (and for which he served as secretary for its first 23 years). Since then, more than 2,800 bachelor's, 1,000 master's, and 350 doctoral degrees have been awarded in chemical engineering at Poly.

THE OTHMER YEARS

In 1932, then-28-year-old chemical engineer **Donald F. Othmer** was hired into Olsen's department, after an impressive five years of work at Eastman Kodak in Rochester, N.Y.

Kodak was the world's largest manufacturer of cellulose acetate, a key ingredient in photographic film. A critical step in creating cellulose acetate is concentrating the acetic acid used in production. While in Kodak's employ, Othmer was tapped to find ways to increase the acetic acid concentration in various sources available to the company. Initially knowing little about the subject, but always curious, Othmer designed an experimental device to observe how acetic acid is distilled. The apparatus he built became famous as the Othmer Still and continues to be used to study the properties of mixtures being distilled. The early version of the still was typical of Othmer's hands-on, low-cost approach to science: He not only conceptualized and designed the apparatus, but also learned glass-blowing so that he could build it himself.

The Othmer Still allowed chemists and engineers to mea-



The Chemical Engineering Laboratory about 1919.

sure accurately for the first time concentrations in the vapor and liquid phases in equilibrium.

Othmer also contributed greatly to the science of azeotropic distillation, which introduces a third chemical during the distillation process to improve the purity of the product and reduce energy consumption. Thanks to Othmer, distillation is now a science. His geometrical and mathematical instincts were applied further to devise a figure in which the effects of temperature on vapor pressure of various compounds could be correlated as straight lines on a single sheet of paper, the now-famous Othmer plot.

As a well-known chemical engineer, Othmer succeeded to the chairmanship in 1937 and remained head of the department until 1961, when he stepped down to devote more time to teaching and research. He has authored hundreds of articles and held numerous patents for chemical engineering applications. Around 1945 **Raymond E. Kirk**, head of the Department of Chemistry, and Othmer, heading the Department of Chemical Engineering, decided to embark on a project as co-editors of an encyclopedia that would be a comprehensive guide to industrial chemistry and chemical engineering. The *Kirk-Othmer Encyclopedia of Chemical Technology* is now in its 5th edition and comprises 27 volumes. It is the first place chemists and chemical engineers turn when they are starting a new project. It has everything from the commonplace to the esoteric, from how to make batteries and beer to how to reduce nitrobenzene. A set may be found in the library of virtually every major university in the world.

When Othmer died in 1995 he bequeathed more than \$175 million dollars to the Polytechnic, which remains as of today the largest donation ever given to the university. Much of the gift went to improving and expanding the university labora-

tory and classroom facilities, with some to construction of a new dorm and gymnasium. An interesting side note: If the remaining professors had joined Othmer 30 years earlier in the investment club he started at Poly—based on the advice of a family friend named Warren Buffet—they all would've been rich; but even sharing a fraction of the membership fee of \$25,000 would have been rather difficult for a faculty member in those days.

Don Othmer supervised and inspired more than 60 doctoral students, many of whom went on to distinguished careers in their own rights. He supervised research in the fields of thermodynamic property estimation, distillative and extractive separations, fluidized bed design, and energy optimization. Having no biological children, he was quoted as saying he regarded himself most fortunate to have been blessed with so many brilliant “academic children” whom he could recognize with almost-paternal pride. One of Othmer's former students was **Ju Chin Chu**, who from 1950 to 1966 supervised fundamental distillation experiments on more than 100 industrially important chemical mixtures. Chu, in turn, must have passed along a high regard for research and genes as well: His son, **Steven Chu**, won the Nobel Prize in Physics in 1997.

Speaking of Nobel Prize winners, a corecipient of the 1995 Nobel Prize in Physics, **Martin L. Perl**, earned his chemical engineering bachelor's at Poly in 1948 (followed by a Ph.D. from Columbia). Perl was honored for the discovery of the tau lepton, one of nature's most remarkable subatomic particles with a mass 3,500 times that of the electron. In 1982, Perl's promise had already been recognized closer to home: That year, he was awarded the Wolf Prize for Physics for the Class of 1948.

In the '50s Othmer was able, through fund raising and departmental equipment gifts from industrial colleagues, to persuade **Warren L. McCabe** to come to Poly and become administrative dean. A leading educator and consultant formerly at Cornell University, McCabe is, of course, famous for the McCabe-Thiele diagrams of binary distillation, as well as being coauthor of *McCabe, Smith, and Harriott's Unit Operations of Chemical Engineering*.

Othmer already had a master craftsman of laboratory equipment on staff, **W. Fred Schurig** (Poly '33, '35, and '46) who constructed one of the finest teaching laboratories in America—Poly's Unit Ops Laboratory. While at Poly and after he retired, Schurig designed and built laboratories for many schools throughout the Americas. Schurig became known for his discipline and attention to detail, which he later attributed to Othmer's influence.

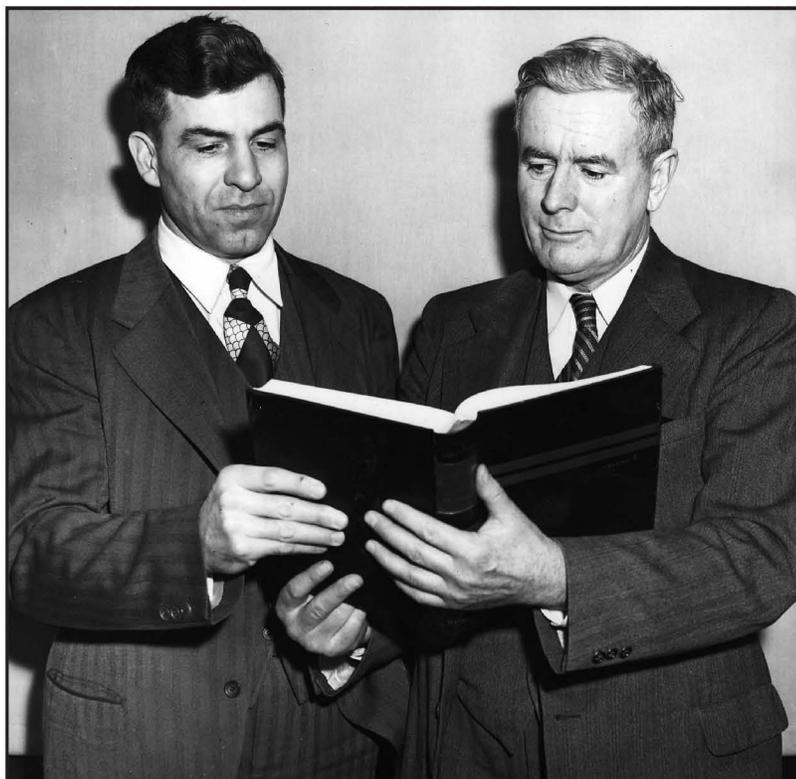
Perhaps the most famous of Othmer's doctoral students, **Joseph J. Jacobs**, also earned all three of his degrees at the Polytechnic, receiving his Ph.D. in 1942. Jacobs developed a system that could manufacture soap in 15 minutes compared to the traditional process that required between three and

seven days. Jacobs was an assistant professor at Polytechnic for a while and then headed west to San Francisco to take a position assisting in the engineering of liquid fertilizers. After doing consulting work for two years at Kaiser Aluminum and Chemical Company—at which he helped develop caustic soda—Jacobs started his own business. In 1947, he founded Jacobs Engineering Group Inc., an international firm that *Fortune* magazine ranked No. 1 in 1999 as the most admired engineering and construction company. In addition to authoring numerous articles on chemical engineering and economics, Jacobs made substantial contributions to the study of social issues—including aging parents of adult children—and authored two autobiographies. He was recipient of the United Engineering Society's 1983 Herbert Hoover Medal, which recognizes the civic and humanitarian achievements of professional engineers. The university also established the Joseph J. and Violet J. Jacobs Chair in Chemical Engineering, and in 2002 opened the Joseph J. and Violet J. Jacobs Building on campus, housing a full gymnasium and athletic center as well as state-of-the-art laboratories and classrooms.

Another well-known doctoral student of Othmer, **Gerhard Frohlich**, earned his Ph.D. in chemical engineering at Poly in 1957. He was the second member associated with the Polytechnic to become president of AIChE, elected in 1999. Earlier he had been named corporate vice president and general manager of Central Engineering at Hoffman-La Roche, where for many years he engaged in the development, design, and construction of chemical and pharmaceutical facilities. In commenting on the importance of AIChE, Frohlich said, “We must think globally, accept cradle-to-grave stewardship of products, and strive for sustainable development. Professional societies can lead the way by facilitating dialogue among industry, government, academe, and the public. By working together in new and more flexible ways, using renewable resources, and learning from advances in chemistry and biotechnology, we can make products that enhance the quality of life and protect the environment. If we commit to doing so, the new millennium looks bright indeed.”

Yet another of Othmer's students, **Robert F. Benenati**, had a long and successful career as a professor who challenged students to do more than they ever thought possible, particularly in his design class. **Warren Seider**, a Poly graduate now at the University of Pennsylvania, is in turn one of Benenati's former students, and is coauthor of the major design text *Product and Process Design Principles*, now in its 2nd edition.

In the '60s and '70s **James J. Conti** (Polytechnic '54, '56, and '59) and **Irving F. Miller** were department heads through a financial crisis, in which PIB merged with the NYU school of engineering to form the Polytechnic Institute of New York, with its main campus remaining at the Brooklyn site. In 1985, the school was renamed Polytechnic University.



Below, Don Othmer poses with a gold-plated version of the invention he created in 1928, the Othmer Still. Left, Othmer is seen with Raymond Kirk, head of Poly's chemistry department circa 1945 and co-editor of the pair's comprehensive encyclopedia, now in its 5th edition.



Rounding out the era, **Leonard Stiel** has carried the Othmer tradition into the computer age; his work is cited widely in the literature of thermodynamic and transport properties of fluids and mixtures. Stiel officially retired a few years ago but now as a research professor he's still very active at Poly in education and as a consultant.

THE POLYMER CONNECTION

In the early part of the 20th century, many prominent chemists dismissed the idea that molecules with molecular weights in the thousands or millions could exist. Today, polymers are everywhere, in everyday materials such as plastics, nylon, and rubber. The year 1939 marked the introduction of a polymers course in the chemical engineering department. That year, chemical engineering professor **Paul F. Bruins** joined Poly from the University of Iowa and offered the first graduate course in polymer technology in the United States, paving the way for what has become one of the most famous polymer programs in the world. Bruins was affectionately called the "walking encyclopedia" of plastics, and he wrote and edited extensively. He was known to take his colleagues for a spin in his small aircraft during the day and return in time to teach his polymer course in the evening.

Much of today's widespread acceptance of polymers, their chemistry, and their engineering is the result of work by the Polymer Research Institute (PRI) of Polytechnic University. **Herman Mark**, a pioneer in the study of giant molecules, established the PRI in 1964. The institute brought together a

number of polymer researchers to create the first academic facility in the United States devoted to the study and teaching of polymer science. Many scientists associated with the institute later went on to establish polymer programs at other universities and institutions, contributing significantly to the development and growth of what has become a vital branch of chemistry, engineering, and materials science. Under Mark's leadership, the institute became the premier U.S. destination for polymer chemistry, attracting students from all over the world. But its effect wasn't limited to simply establishing the importance of polymer chemistry and contributing many of its fundamental discoveries—like colonists, PRI alumni went on to found a number of polymer institutions at other locations.

The American Chemical Society (ACS) recognized the institute's pioneering efforts by designating it a National Historic Chemical Landmark. Such designations recognize important places, discoveries, and achievements in the history of chemistry. Other landmarks have included Joseph Priestley's Pennsylvania home, penicillin, and the National Institute of Standards and Technology. PRI holds a special place in ACS Past President **Eli M. Pearce**'s heart, as from 1982 to 1996 he served as its director. Pearce started at Polytechnic in 1973, had a joint appointment in the Departments of Chemistry and Chemical Engineering, and is currently a university research professor. Pearce is confident about PRI's future: "When you read the [National Research Council report 'Beyond the Molecular Frontier'], it's clear that the most exciting developments in science and technology are occurring at the interfaces. Over the years, considerable contributions were made to the engineering side of polymerization research and education."



*Acclaimed alumnus
Dr. Joseph Jacobs with a blueprint
for one of the many important
projects in which he was a partici-
pant. In addition to establishing a
Joseph J. and Violet J. Jacobs Chair
in Chemical Engineering, in 2002 the
university opened the Joseph J. and
Violet J. Jacobs Building on campus.
It houses a full gymnasium and ath-
letic center as well as state-of-the-art
laboratories and classrooms.*

Two other Poly engineering faculty who have made long-term contributions to the polymer-engineering field are **Chang Dae “Paul” Han**, a former department head (1974-82), and **Jovan Mijovic**, present department head. Han published widely in polymer and chemical engineering journals, and wrote two books: *Rheology in Polymer Processing* and *Multiphase Flow in Polymer Processing*, both published by Academic Press. Mijovic in the course of his illustrious career has published widely in polymer journals and supervised dozens of doctoral students in the study of polymeric materials properties and states, and more recently has been investigating complex chemical and biosystem dynamics, nanotechnology, and nano-materials. He has led the department into the chemical and biological engineering era while continuing his yeomanlike efforts as a dedicated, distinguished teacher and researcher. He’s committed to maintaining Poly’s tradition of excellence.

THE ENVIRONMENTAL SCIENCE AND ENGINEERING CONNECTION

The Polytechnic has performed many research investigations concerned with the understanding of fluidized bed fundamentals. Fluidization is used widely in petroleum refining, power generation, and in the chemical industry. **Frederick Zenz** received his Ph.D. at Poly in 1961 and taught a graduate course throughout the ’60s entitled “Fluidization,” eventually writing and publishing the seminal work *Fluidization and Fluid Particle Systems* with Othmer.

In the early portion of his career, Poly’s **Edward Ziegler** earned an international reputation for his research in fluidized

bed transport and reaction engineering modeling. His heat transfer model is used in the design of fluidized bed coal combustors. Ziegler, along with former Poly professor **Rutton Patel** (now with ExxonMobil) supervised students in the fluid bed research area, and the two often became members of each other’s guidance committees.

Later Ziegler’s interests turned toward environmental applications and specifically air pollution engineering control. He has co-edited the 5th Edition of the *Pfafflin-Ziegler Encyclopedia of Environmental Science and Engineering*, published in January 2006, and authored a number of its articles. He started on the encyclopedia’s first edition some three decades ago, together with his co-editor **James Pfafflin**—a former member of Poly’s Department of Civil Engineering. Over his career Ziegler has taught more than 1,000 students in the undergraduate lab, and more than 800 graduate students, mainly in his Chemical Reactor Design and Air Pollution Engineering Control courses. He’s been the thesis and project adviser to numerous master’s and doctoral students as well as advising undergrads.

Starting in 1986 **Allan Myerson** headed the department and eventually became dean of the School of Chemical and Materials Science. Myerson encouraged interdisciplinary studies between the engineering and science departments. He also was active in crystallization and nucleation research and edited the *Handbook of Industrial Crystallization*.

A ‘WORLD CLASS’ UNIT OPERATIONS LABORATORY, REVISITED

A major renovation of the chemical engineering lab took place in 2001, when **Walter P. Zurawsky**’s considerable transport phenomena knowledge, research experience at AT&T Labs, and equipment construction skills were put into play. Professor Ziegler had been teaching the lab for many years after his mentor Fred Schurig retired. With the help of the Othmer gift to the school, Zurawsky and Ziegler planned a student-friendly, state-of-the-art experimental teaching facility with new distillation columns, process control equipment, a

Chemical Engineering Education

controlled fermenter, and membrane separations experiments. The new, highly automated distillation experiment is, by the way, currently used to investigate the efficiency of concentrating acetic acid (shades of Donald Othmer?) using sieve trays and packed columns. The senior CBE students perform 20 experiments in their final two semesters. Many of the scaled-down versions of traditional chemical engineering operations were retained and are still used to study classical theories and industrial correlations, but with modern instrumentation. A computation room was fitted with the latest PCs having Lab View, Microsoft, and MatLab software to help store, transmit, and analyze the data. The ASPEN Engineering Suite is available to all CBE students on their local network, primarily for use in the senior design courses.

NEW PATH: CBE—PRESENT AND FUTURE

Over the past 40 years, chemical engineering curricula have embraced an engineering science paradigm that spans from molecular-level interactions and transformations to large-scale systems. Indeed, it is an appreciation of, and a willingness to work over, many decades of scale that is one of the distinguishing traits of the chemical engineering discipline. This ability to adapt to work on many scales has allowed chemical engineers to have productive interactions with a wide range of other science and engineering disciplines, and will be essential for the application of engineering principles to biologically based processes. The rising need to convert advances in biology into new processes and new industries makes it imperative that we adopt biology as an enabling science.

Interest in integrating biology and chemical engineering, or CBE, is growing nationwide. For example, the number of biologically oriented presentations at the AIChE annual meetings increased from less than 10% to close to 50% in only four years. Many chemical engineering departments across the country have changed names to reflect a growing interest in, and overlap with, biology (examples include Johns Hopkins, Cornell, the University of Pennsylvania, the University of Wisconsin-Madison, Northwestern, and RPI). Many such departments have started to require a biology course as part of their curriculum, but there are still very few that have made a full commitment to developing a curriculum in which biological systems and processes are fully integrated across the curriculum, as we are doing.

Several years ago the engineering faculty within our department reviewed and revised the chemical engineering curriculum to reflect what it felt was the emerging importance of biology. The specific aim was to develop an exemplary educational program (B.Sc.) in chemical and biological engineering that builds on the traditional strengths and paradigms of chemical engineering while embracing biology as a pillar along with mathematics, chemistry, and physics. So substantive are the changes that we, too, undertook a program name change from chemical engineering to chemical and biological

engineering. The CBE program was initiated with the freshman class of 2003.

We firmly believe that chemical engineering principles can and must be applied to biological systems and to the development of new processes based on biology. The task we face in implementing this new curriculum is substantial, but we are eminently qualified and confident of the success of the proposed program.

The courses for our new CBE program are shown in Table 1 (next page). The program has been approved by the faculty of our department, by the faculty of Polytechnic University, and by the State of New York. By careful choice of electives and several course substitutions, CBE students can adjust their schedules to satisfy medical school requirements if they have an interest in pursuing medicine as a career.

The task we face is to meld, as seamlessly as possible, systems and processes of biological relevance into our engineering curriculum. We regard the systems-oriented, multiscale approach to problems that is the hallmark of chemical engineering as the primary strength we have to offer. We believe it is essential that our students remain strong in engineering. It is our further belief that by exposing our students to biology and bio-processes in addition to more conventional chemical processes, we will produce better, more versatile engineers.

As part of our new curriculum, we have introduced required courses in biology and biochemistry and are revising virtually all of our engineering courses to include biological applications and examples. Technical electives in the junior and senior year provide opportunities for elective courses, particularly new electives focusing on engineering in biology such as System Biology, Protein Engineering, and Drug Delivery. Although these new elective courses will be primarily aimed at CBE students, they will be open to other engineering and science students.

We are the only chemical and biological engineering program in New York City and we have seen phenomenal growth in our undergraduate enrollment over the past two years: from 41 undergraduates in 2004 to 110 in early 2006—a whopping 150% increase. The CBE program is acknowledged as the most demanding major on campus. A GPA of 2.5 is required to remain in the major (2.0 elsewhere) and the students' response has been hugely enthusiastic. We have had the highest percentage of students on the Dean's List and named as valedictorians in recent years.

UNIQUE ATTRIBUTES OF THE POLYTECHNIC

Polytechnic provides an important educational opportunity for students who tend to be under represented in engineering. Given our downtown Brooklyn location, our student population has always included a large cross section of the population of Brooklyn and the other boroughs of New York City. As different ethnic groups have immigrated to the United States,

TABLE 1 Chemical and Biological Engineering Curriculum <www.poly.edu/cbe/undergrad/cbe>			
Freshman Fall		Freshman Spring	
MA1014	Calculus I	MA1114	Calculus II
CM1004	Gen. Chemistry for Engineers		Intro to Cell & Molecular Biology
EN1014	Writing & Humanities I	CBE1214	Intro to Chem & Bio Engineering
EG1004	Intro Engineering & Design	EN1204	Writing & Humanities II
Sophomore Fall		Sophomore Spring	
MA2012	Linear Algebra I	MA2112	Multi-variable Calculus A
MA2132	Ordinary Differential Equations	MA2122	Multi-variable Calculus B
PH1004	Introductory Physics I	PH2004	Introductory Physics II
CBE2124	Analysis of Chem & Bio Processes	CS1114	Intro to Prog. & Problem Solving
CM2234	Industrial Organic Chemistry	CM2514	Chemical & Biological Equilibria
Junior Fall		Junior Spring	
CM3314	Biochemistry I	CBE3324	Chem & Bio Separations
CBE3103	Math Methods for Chem & Bio Eng.	CBE3214	Chem & Bio Reactor Engineering
CBE3314	Physical Rate Processes		Technical Elective
HI2104	Modern World History		HU/SS Elective
CBE3622	Chem & Bio Eng. Thermodynamics		
Senior Fall		Senior Spring	
CBE4113	Engineering Laboratory I	CBE4123	Engineering Laboratory II
CBE4413	Process Dynamics & Control	CBE4623	Chem & Bio Process Design II
CBE4613	Chem & Bio Process Design I	CBE4713	Engineering Polymeric Materials
	HU/SS Elective		Engineering Elective
	Technical Elective		HU/SS Elective

Poly's student population has changed, always mirroring the ethnic mix of the city.

In addition to the ethnic diversity that is part of Polytechnic, we are proud to note that over the past de-

cade nearly 50% of the students who have graduated from our chemical engineering program are female. We fully expect that this trend will continue with our new program in chemical and biological engineering. Although there have been advances nationwide, women are still grossly under-represented in engineering.

Polytechnic is a private university, but our role in the New York region is, de facto, one that would be expected of a public university. As shown in Table 2, we educate a much greater percentage of students from lower-income households than the state university system does. *Washington Monthly* ranked Polytechnic University second in the nation (out of 245 national universities) in social mobility.

TABLE 2 Student Family Incomes: Polytechnic and the State University of New York			
Annual Income	< \$20k	\$20k to \$80k	> \$80k
Polytechnic	28.4%	51.6%	20%
SUNY	13.0%	31.0%	56%

Our location in New York provides us with exceptional opportunities. We are in a region with many excellent biomedical institutions including Rockefeller University, Memorial Sloan-Kettering Cancer Institute, SUNY Downstate Medical Center,

and Albert Einstein College of Medicine, to mention a few. Adding to the list, a new \$700 million science park on the grounds of Bellevue (just across the East River in Manhattan) was announced on the front page of *The New York Times* a few weeks ago. The focus of this new East River Science Park will be the biotechnology industry. The facility is being developed by Alexandria Real Estate Equities, Inc.—whose chairman of the board, **Dr. Jerry Sudarsky**, is a Polytechnic alumnus and a member of the Board of Trustees of Polytechnic. These excellent medical institutions and the new science park will provide our graduates with avenues for continued education, opportunities for collaboration, and potential employment.



Modern buildings on campus include Dibner Library on Metrotech Commons, far left, and the Othmer Dormitory, left.



Edward Ziegler

CURRENT FACULTY

The explosive potential of CBE has been recognized by the Polytechnic trustees, our new president, **Jerry MacArthur Hultin**, and the members of the administration. These

pivotal individuals have made a major commitment to our department's continuing growth. Three years ago, **Jose M. Pinto** joined our faculty from the University of Sao Paulo in Brazil. Pinto received his Ph.D. from Carnegie-Mellon and is interested

in modeling and optimization of chemical and biological processes and systems biology. In fall 2004, **Stavroula Sofou** joined the faculty. Sofou received her Ph.D. from Columbia University in New York City and spent three years as a post-doc at the Memorial Sloan-Kettering Cancer

Research Center. Her principal interest focuses on the use of engineering principles for drug delivery for cancer cure.

We announced two additional faculty positions in fall 2006.

Rasti Levicky, formerly of Co-



Jovan Mijovic



Jose Pinto



Stavroula Sofou

lumbia University, was named the Donald F. Othmer Assistant Professor of Chemical and Biological Engineering. Levicky received his Ph.D. from the University of Minnesota and has a strong interest in the field of biological polyelectrolyte

systems, nanosized micro array biosensors, and bio-diagnostics. Jin Ryoum Kim is the Joseph J. and Violet J. Jacobs Assistant Professor of Chemical and Biological Engineering. He got his Ph.D. from the University of Wisconsin at Madison. His interest is in the area of protein engineering and particularly those that aggregate and cause Parkinson's and Alzheimer's diseases.

Finally, we are very proud to announce that on Jan. 1, 2006, our department was officially renamed The Othmer-Jacobs Department of Chemical and Biological Engineering, in recognition of enormous contributions to our discipline made by these two chemical engineering giants. Visit our Web site: <<http://www.poly.edu/cbe>>.

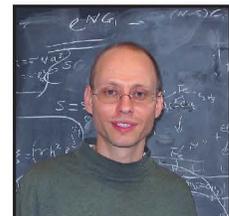
ACKNOWLEDGMENTS

For practical reasons, this article mentions only a few of the people that are part of the history of chemical engineering at the Polytechnic. We would like to acknowledge those dedicated present and former professors, students and alumni, and their supporters, without whom Polytech would never have attained its successful international reputation.

We thank our colleagues in the department for their help writing this article, and greatly appreciate the efforts of **Christopher Hayes**. □



Jin Ryoum Kim



Rasti Levicky

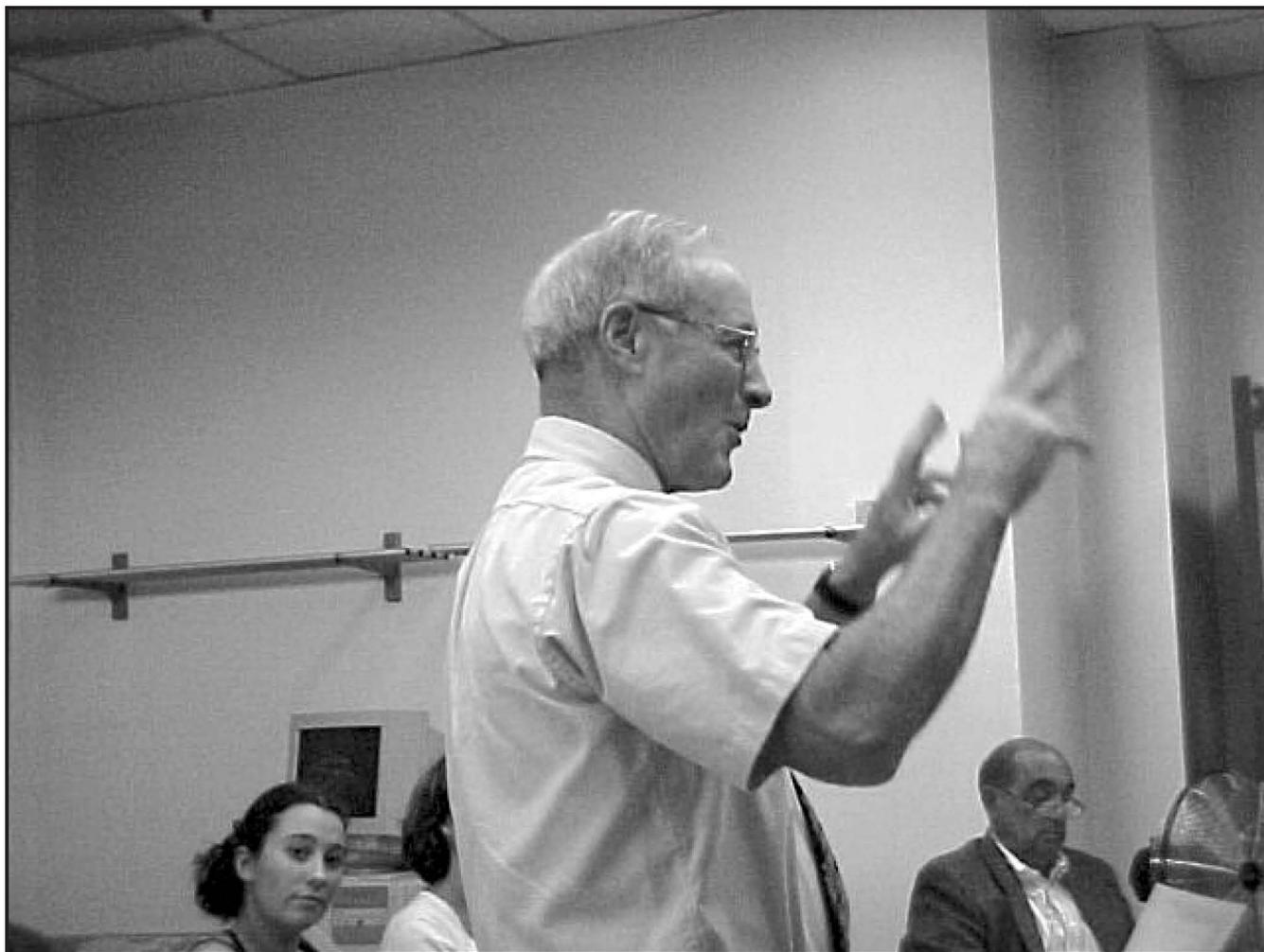


Leonard Stiel



Walter Zurawsky

Joseph Reynolds *of Manhattan College*



HELEN C. HOLLEIN
Manhattan College • Riverdale, NY 10471

Joseph Reynolds earned a bachelor's degree in chemistry from Catholic University of America in 1957 and a Ph.D. degree in chemical engineering from Rensselaer

Polytechnic Institute in 1964. He taught high school chemistry and physics full time at LaSalle Academy in New York City from 1957 to 1959, then taught college chemistry part time for Catholic University (Troy extension) while pursuing his doctoral degree at RPI. Joe excelled as a student and was

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Chemical Engineering Education



Joe, at right, posing with Lou Theodore, his long-time friend, collaborator, and fellow faculty member.

inducted into the Phi Beta Kappa, Tau Beta Pi, Sigma Xi, and Phi Lambda Upsilon honor societies. His many accolades include listings in American Men and Women in Science, Who's Who in Technology Today, Who's Who Among America's Teachers, International Who's Who in Engineering, Who's Who in the East, and Who's Who in Engineering.

Since 1964, Joe has been a member of the chemical engineering faculty at Manhattan College, where he holds the rank of professor of chemical engineering. It caused some excitement among Joe's colleagues when Br. Thomas Scanlan was appointed president of Manhattan College, because Br. Thomas had been one of Joe's students in a freshman chemistry course that he taught in Troy. (Fortunately, we understand that Br. Thomas earned an "A" in the course.)

Joe served as chairperson of the Department of Chemical Engineering for seven years (1976 to 1983), and also was called upon to serve as acting chair for brief stints totaling another two and a half years while his successors were on sabbatical leave. As part of his academic duties, Joe has served for many years as moderator of the student chapter of the American Institute of Chemical Engineers (AIChE), and has been president of the college's Sigma Xi Chapter. He has also served on a large number of college committees, but says his favorite is the Board of Trustees' Facilities Planning Committee because this membership ensures his invitation to the President's Christmas Dinner (best wine selection and food service, by far).

Since completing his doctoral research at RPI on "The Effect of High Pressure on the Infrared Spectra of Solids," Joe has collaborated for more than 30 years with Dr. Louis Theodore at Manhattan College on various environmental research projects. Many of Joe's books and research publications include

undergraduate students as coauthors. His current research interests are in the air pollution control and hazardous waste incineration areas. He has coauthored numerous text/reference books, including *Introduction to Hazardous Waste Incineration*, 2nd Edition (2000), *Accident and Emergency Management* (1989), and *Handbook of Chemical and Environmental Engineering Calculations* (2002), all from Wiley-Interscience, New York. He has developed computer software, which is available commercially and currently used in the EPA's training program, to simulate hazardous waste incinerator (HWI) performance. His publications include problem and solution workbooks that he uses in the courses that he teaches at the college, as well as EPA training manuals for the HWI software. Joe has also served as a consultant for several private companies and is presently a consultant/expert witness for the Department of Justice and the U.S. Environmental Protection Agency. He has been active for most of his career in the Air and Waste Management Association (AWMA), formerly the Air Pollution Control Association (APCA), where he presents papers and chairs sessions at annual meetings as well as coordinating associated continuing-education programs.

TEACHING TAKES PRECEDENCE

Manhattan College offers both B.S. and M.S. degrees in chemical engineering, and Joe has always taught the undergraduate courses by choice. He has taught the Engineering Materials course and directed its associated laboratory for his entire career at the college, and currently teaches Process Calculations, Engineering Thermodynamics, Fluid Mechanics, and Computer Aided Simulation and Design in Chemical Engineering. During his tenure, he has taught nearly every course that the department offers (or previously offered) including Chemical Engineering Thermodynamics, Heat

*Proudly posing
with students
at a poster
competition.*

Transfer, Chemical Engineering Laboratory I-II, Physical Metallurgy, Physical Chemistry I-II, Computer Methods in Chemical Engineering, Computer Science and Programming, and Fortran Programming for Chemists.

In the classroom, Joe is very much an “in your face” kind of teacher. He teaches several of the required sophomore courses for chemical engineering majors, giving out grades from “A” to “F,” as deserved. The good students stay, the others repeat or change majors. The current seniors have created a bulletin board with pictures and the facts as they see it for the chemical engineering faculty. Their advice for students of Dr. Reynolds’ classes includes: “Participate as much as possible. This will lessen your chance of being randomly called on during class.”

Joe’s courses are well organized and fast paced. He sets high standards, gives fair-but-tough tests, and assigns homework due at every class. In the old days, he distributed the homework assignments for the entire semester on day one, but when the Internet was relatively new, he forced the students to use it by sending out assignments via e-mail only. The seniors advise, “check your e-mail every day, at least twice a day. There will always be something new in there.” This practice has the added advantage of getting the students to read messages about AIChE meetings and parties, which gets them involved in departmental activities from freshman year on.

Joe is one of the teachers who makes effective use of the computer projector and PowerPoint slides for each of his lecture courses: He expects students to listen and respond during his presentation instead of just madly copying information. His PowerPoint presentations are available for all of his students through the course Web sites on the Blackboard system. Many of Joe’s current and former students credit him as being a truly outstanding teacher, a fact that is supported by his numerous teaching awards and consistently excellent course and teacher evaluations.



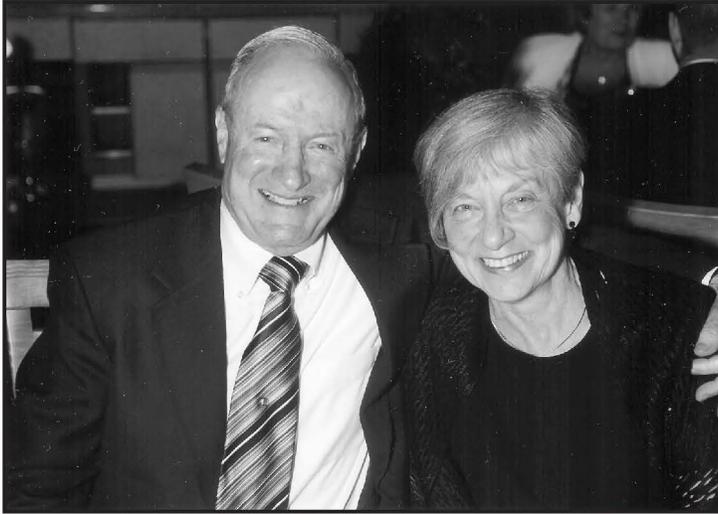
Joe’s focus on excellent teaching must have set a good example, because several of his former students also pursued careers in academia. Among them are Dr. Ruben Carbonell (B.E. 1969), now KoSa Professor of Chemical Engineering at North Carolina State University; Dr. Sonia Kreidenweis (B.E. 1983), now professor of atmospheric science at Colorado State University; Dr. John Blaho (B.E. 1983), now associate professor of microbiology at Mount Sinai School of Medicine; and Dr. Marco Castaldi (B.S.ChE 1992), now assistant professor of earth and environmental engineering at Columbia University.

His former students turned academicians credit Joe in various ways for encouraging their graduate education and influencing their decision to pursue research and teaching at the college level as a profession. Br. Thomas participated as an undergraduate in Joe’s research at RPI, and credits this early experience with giving him “an understanding of the way that research and scholarly activities reinforce teaching and vice versa.” Sonia Kreidenweis co-authored her first publication with Drs. Reynolds

and Theodore in the *Journal of the Air Pollution Control Association*, based on her undergraduate research at Manhattan College. She credits Joe as being “the first to suggest [that] I apply to graduate school and go on for a Ph.D.”—a degree she subsequently completed at California Institute of Technology. Ruben Carbonell says that as an undergraduate, he “looked up to Dr. Reynolds as a role model of an excellent professor,” which greatly influenced his decision to pursue a career in college teaching.

“Participate as much as possible. This will lessen your chance of being randomly called on during class.”

—Advice from seniors to students planning to take Reynolds’ class.



Top left, Joe and wife Barbara. Top right, Barbara and daughter Megan on a family trip to Toledo, Spain—where both Reynolds daughters got to practice their fluent Spanish. Right, Joe and daughter Marybeth undertaking a favorite family activity—skiing—at Steamboat Springs, Colorado.



OUTSIDE INTERESTS

All is not academics for this overachiever, however. Joe's favorite recreational activities include skiing and jogging. He can be seen early mornings jogging around his Bronx neighborhood near the college. His equally active family—wife Barbara and daughters Megan and Marybeth—has accompanied him on the annual Manhattan College ski trip every January since the girls were infants. The foursome has also made the AWMA (APCA) meetings in June an annual event. One of Barbara's favorite activities is international travel, and the family has made so many trips to Ireland that Megan and Marybeth recently obtained dual citizenship.

Joe is as proud of his family's achievements as of his own. Barbara has retired from Fordham Preparatory School in the Bronx after 35 years of teaching. Megan and Marybeth both earned baccalaureate degrees in chemical engineering with honors from Manhattan College, so Joe is one of our most enthusiastic alumnae parents. Megan recently received a master's degree from Thunderbird, the Garvin School of International Management in Phoenix. After working in Spain for the pharmaceutical industry, she is currently working for Merck in New Jersey. Marybeth completed her master's in

Public Policy at Georgetown University and currently works for Cancer Care in New York City. Both daughters are fluent in Spanish and have studied other languages as well, *i.e.*, Russian for Marybeth and Portuguese for Megan.

THE MOST REWARDING PART

Joe is well known for his quick smile and easygoing manner, as well as for his endearingly annoying habit of correcting everybody's grammar—often in midsentence. The seniors say, "Use proper English. He will call you on it every day!" This applies equally to his faculty colleagues.

Joe's story is unusual in that he is an outstanding teacher and a respected researcher at a primarily undergraduate institution. When he was honored with a Bonus et Fidelis Medal on his 25th anniversary at Manhattan College, he was interviewed about his experiences. Asked about the most rewarding part of his career, his response was immediate: working with students. □

THE CHEMICAL ENGINEERING BEHIND HOW POP GOES FLAT: *A Hands-On Experiment for Freshmen*

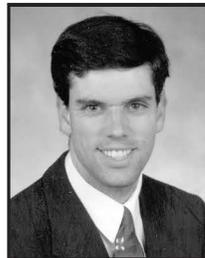
KEITH L. HOHN

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One of the endemic problems specifically in chemical engineering, as well as in the field of engineering in general, is the low retention rate of undergraduate students. This attrition is especially noticeable in the first two years of undergraduate studies, as roughly 50% of freshmen entering chemical engineering do not make it to their senior year.^[1] While students have varying reasons for transferring out of science and engineering fields, one of the most common is a loss of interest in science and engineering.^[2] In most chemical engineering departments, students do not take a core chemical engineering course until their sophomore year, and don't become immersed in chemical engineering until their junior year. This means that underclassmen who switch majors due to a loss of interest in science and engineering do so without a good understanding of chemical engineering.

To combat the retention problem, many chemical engineering departments require an introductory course in chemical engineering during the first semester of the freshman year.

Typically these courses serve to introduce students to the department and its procedures, and give a broad overview of some applications in chemical engineering. From a brief survey of course descriptions and syllabi found on the Internet, it appears that many of these courses use field trips to chemical plants and presentations by guest speakers to give students more of a perspective on the discipline. While these are excellent activities to which students in chemical engineering can be exposed, one problem is that they are,



Keith Hohn is an associate professor of chemical engineering at Kansas State University. He received his bachelor's degree from the University of Kansas and his Ph.D. from the University of Minnesota, both in chemical engineering. His research interests are heterogeneous catalysis and its application in hydrocarbon conversion and hydrogen generation.

for the most part, passive activities. Students are generally hearing someone tell them what chemical engineering is or are seeing pieces of process or laboratory equipment. They are not touching, designing, or building anything. Hands-on activities are relatively rare, though some departments have used them successfully.^[3-7]

There are numerous reasons why hands-on projects are not incorporated into freshman chemical engineering courses more often. First of all, freshmen do not generally have the background to apply many chemical engineering principles. Secondly, it is difficult to package a true chemical engineering application into something that freshman students can manipulate since chemical engineering frequently deals with very large and sometimes hazardous processes. Finally, many interesting activities would require extensive laboratory and calculational time (on the order of the laboratory experiments taught in chemical engineering lab courses). The requirement for a useful hands-on activity that could be incorporated into a freshman course is one that is interesting, safe, easily understood by students with limited chemical engineering knowledge, fairly simple, and capable of being completed in a reasonable amount of time. This paper details such an experiment that in fall 2003 and fall 2004 was incorporated into a freshman chemical engineering course at Kansas State University (CHE 110, Current Topics in Chemical Engineering). This experiment has students study the often-encountered phenomenon of carbonated soft drinks that have lost their fizz (here in Kansas, we call that flat pop). Students design and carry out experiments to study one aspect of this phenomenon. The efficacy of this exercise in teaching students what chemical engineering is and in increasing student enthusiasm for studying chemical engineering was measured by a semester-end survey.

BACKGROUND

Freshman students are generally familiar with the phenomenon of carbonated beverages going flat, and have some intuitive understanding as to why it occurs. Most will know that the loss of carbonation leads to a flat beverage, and some will recognize that carbonation is simply the absorption of CO₂ into the liquid phase. What students will not be familiar with are the chemical engineering principles behind how pop goes flat and how chemical engineers use many of these principles to design chemical processes.

There are numerous chemical engineering principles involved in the loss of carbonation. This is truly a rich mass-transfer problem. Loss of carbonation depends on two factors: the gas-liquid equilibrium for CO₂ and the rate at which mass transfer of CO₂ from the liquid to the gas phase occurs. The gas-liquid equilibrium is represented by Henry's Law:^[8]

$$H = P_{\text{CO}_2}(\text{g}) / C_{\text{CO}_2}(\text{l}) \quad (1)$$

where $P_{\text{CO}_2}(\text{g})$ is the CO₂ partial pressure in the gas phase, $C_{\text{CO}_2}(\text{l})$ is the concentration of CO₂ in the liquid phase, and H is the Henry's Law constant.

Given enough time, CO₂ will leave the liquid solution and enter the gas phase until the above equilibrium relationship is fulfilled. Temperature plays an important role, as the Henry's Law constant decreases with increasing temperature. For carbonated beverage bottles left closed for long periods of time, equilibrium is the most important factor in how the carbonated beverage goes flat. The volume of the head space is clearly important here, as the partial pressure in the entire volume must satisfy the equilibrium relationship. Large head space volumes lead to a large loss of CO₂ from the liquid.

Mass transfer kinetics can be important in such situations. There really are two types of mass transfer occurring in this system: mass transfer of CO₂ from the liquid to the gas and mass transfer of CO₂ through the bottle to the outside atmosphere. For the standard polymer used to construct carbonated beverage bottles, polyethylene terephthalate, the rate of mass transfer of CO₂ through the bottle is small. This would not be the case, for instance, if low-density polyethylene was used to make the bottle. The rate of mass transfer from the liquid to the gas becomes important in loss of carbonation if the bottle is opened and closed often within a short period of time. In this case, there is not enough time to reach equilibrium, so the CO₂ lost from the liquid phase is the amount that went into the gas phase in the time between openings. Mass transfer of CO₂ into the gas phase can be represented by:^[8]

$$N_{\text{CO}_2} = K_G (P_{\text{CO}_2} - P_{\text{CO}_2}^*) \quad (2)$$

where:

$$P_{\text{CO}_2}^* = HC_{\text{CO}_2} \quad (3)$$

N_{CO_2} is the flux of CO₂, P_{CO_2} is the partial pressure of CO₂ in the gas phase, K_G is the gas-phase mass transfer coefficient times the mass transfer area, $P_{\text{CO}_2}^*$ is the partial pressure of CO₂ at the gas-liquid interface, and C_{CO_2} is the concentration of CO₂ in the bulk liquid.

IMPLEMENTATION

This activity was incorporated in CHE 110 (Current Topics in Chemical Engineering) for fall 2003 and 2004. This is a one-hour introductory chemical engineering course that freshmen and transfer students are required to take for a letter grade. Four of the 16 contact hours were spent on the CO₂ absorption activity. The remaining time was dedicated to lectures on curriculum requirements, advising and enrollment, how to seek internships and full-time positions, applications of chemical engineering, and field trips to a dairy processing facility and the chemical engineering laboratories.

Students were presented with the topic of carbonated beverages going flat by having a number of students take the "Pepsi challenge," in which they sampled two different

beverages and determined which tasted better. To show why carbonation is important, one of the beverages was flat while the other was fresh. Brief discussion of what made the fresh beverage better ensued. This was followed by a discussion of why carbonated beverages go flat, which introduced the idea of CO_2 absorption and set up a discussion of mass transfer and gas/liquid equilibrium.

Students were then shown two ways to quantify the mass transfer of CO_2 from carbonated beverages. The first method was based on an article by Crossno.^[9] Briefly, a balloon filled with 50 ml of 1M NaOH was affixed to a flask containing 150 ml of a carbonated beverage. The beverage was stirred and left for ~24 hours to drive the CO_2 out of solution. CO_2 was adsorbed into the sodium hydroxide solution to form sodium carbonate. Titration of that solution to the first colorless phenolphthalein endpoint neutralized the excess sodium hydroxide and converted all of the sodium carbonate to sodium bicarbonate. Continuation of the titration to the methyl orange endpoint converted the sodium bicarbonate to water and CO_2 . The amount of HCl required to go from the phenolphthalein endpoint to the methyl orange endpoint gave the amount of CO_2 in the carbonated beverage.

The second method was to replace the original bottle cap with a cap in which a pressure gauge had been placed. This cap allowed the pressure in the head space to be measured as a function of time.

During demonstration of the two methods, laboratory safety procedures were highlighted and a handout was given on these procedures. Following the demonstrations, the students were told to form groups (self-selected) of four or five students. Each group was told that they were to identify and select one research topic related to the mass transfer of CO_2 in carbonated beverages. Several topics were suggested to them, although they were encouraged to brainstorm their own project ideas. They were then instructed to identify what experiments and measurements they needed to do in order to address the research question. They were finally told that they would be required to report their results in both a written and an oral report. Final written reports were turned in the last day of class. Oral reports were given during class time in front of the whole class in the last two or three weeks of the class.

Performance on the project was a major factor in the students' final grade. In the first year of implementation, an overall letter grade was assigned for the reports, which was given roughly equal weight with attendance. In the second year of implementation, the project was assigned 200 points out of a possible 500 points, with the remainder of the points for attendance. Students were required to turn in several reports during the semester to ensure that they were making progress on the project. The reports and their point value are as follows: firing memo (described in the following paragraph), 10 points; description of experimental objectives, 10 points;

detailed experimental plan, 20 points; preliminary results report, 20 points; rough draft of final report, 10 points; final written report, 100 points; oral report, 30 points.

The students were given little information on working in teams the first year, and this led to a few problems (described in the results section). To address this problem in 2004, each team was asked to meet and discuss the team's expectations for individual team members. They were also asked to lay out what specific actions would be taken if students did not meet those expectations, leading up to a possible ultimate action of "firing" the individual. They were then required to write a document (a "firing memo") detailing this discussion and all team members had to sign it. In addition, students were required to rate their peers in a number of areas, such as attendance at team meetings, contribution to reports, and attitude, and turn in their ratings with the final report. Students consistently rated low by their peers received a deduction of their project grade, with the severity of the deduction determined by how low their ratings were.

RESULTS

Because students were allowed to choose their own research topics, topic selection varied. Topics included:

- ① *Does the commercially available Fizzkeeper work?*
- ① *How does temperature affect CO_2 absorption?*
- ① *Estimate the mass transfer coefficient for CO_2 loss from carbonated beverages.*
- ① *Estimate Henry's Law constant for CO_2 in carbonated beverages.*
- ① *Determine effect of different container materials (polyethylene, glass, and PET) on carbonated beverages going flat.*
- ① *Determine how different PET beverage containers affected the loss of CO_2 over time.*
- ① *How does the length of time the cap is left off a bottle affect the rate at which the carbonated beverage goes flat?*

The experiments the students conducted and how they analyzed their data varied for the different projects. Most groups addressed their research question empirically. For example, several groups plotted CO_2 concentration and/or gas pressure vs. time for different conditions (*i.e.*, different temperatures, with and without a fizzkeeper). These groups did not use the mass transfer equations described above.

Other groups relied on the mass transfer equations to address quantitative questions, such as estimating the Henry's Law constant or the mass transfer coefficient. The group that estimated the Henry's Law constant measured concentration of CO_2 in the liquid phase and pressure in the gas phase for several different samples, and attempted to fit these data with

a single value of the Henry's Law constant. The group that attempted to estimate a mass transfer coefficient measured the gas pressure over time after the bottle had been opened and closed (to start with atmospheric pressure). From the known volume in the head space and the measured pressures, they could calculate the change in moles of CO_2 in the gas phase. Next, the students solved Eq. (2) by separation of variables, assuming that the concentration of the liquid (and therefore $P_{\text{CO}_2}^*$) was a constant over time at the value they measured after the mass transfer experiment. They then plotted their experimental data using the resulting equation, and found K_G from this plot. Essentially, they plotted the logarithm of the partial pressure vs. time, which yielded a linear plot, the slope of which was K_G . This analysis assumed that all of the mass transfer resistance was in the gas phase, which likely was not the case. Making this assumption helped in the analysis, however, since the students could readily measure the gas-phase pressure over time.

The titration procedure was problematic for some students. Sometimes students found that the balloon containing NaOH, in which CO_2 was absorbed, had been sucked into the flask when they returned to the laboratory for titration. Sub-atmospheric pressures had apparently been created inside the balloon due to loss of CO_2 from the gas phase, causing the balloon to shrink and eventually completely collapse. Students also reported some problems with getting reproducible results with the titration. These problems were likely due to human error in most cases. There were fewer complaints in the second year, possibly because a longer period of time was given for completion of the project (nearly the entire semester, as opposed to only six weeks) which allowed for more repeat trials.

Student work showed promise, but analysis was often too simplistic or relied on too few data points to draw a conclusion. This provided a good opportunity, however, to present important concepts such as estimating error and the need for a good experimental design with replication. In the second

year, students were asked to lay out a detailed experimental plan for the data they would take to address their research question, and were given feedback on the appropriateness of their plan. In addition, preliminary reports provided more opportunity to give feedback on whether they were analyzing their data properly. Their oral presentations showed a good deal of sophistication, with all groups using PowerPoint presentations with imbedded graphics. It is obvious that they had previously given PowerPoint presentations in high school, as no time was spent teaching about the tool.

ASSESSMENT

Survey Results

A detailed survey was given to the students at the end of the semester to evaluate both the course in general and individual class activities. The results of this survey were used to assess the effectiveness of the hands-on CO_2 absorption experiment in educating freshmen about chemical engineering and increasing their enthusiasm for studying chemical engineering. Table 1 summarizes student responses.

As seen in this table, students generally felt that the CO_2 absorption activity improved their understanding of chemical engineering and increased their enthusiasm for studying chemical engineering. In addition, the CO_2 absorption activity was mentioned by 15 students (out of 36 students who responded) as one of the three most useful activities in the course (along with a field trip to a dairy processing facility and a lecture on biotechnology), and by 17 students as one of the three most enjoyable activities (along with the field trip to the dairy processing facility and a tour of the chemical engineering laboratories). It is interesting, but perhaps not surprising, that the most enjoyable activities had the students going out to see applications of chemical engineering or engaging in a hands-on activity rather than listening to a lecture.

QUALITATIVE EVIDENCE

Most students seemed to enjoy the exercise. The opportunity to work with a "real world" engineering problem energized a number of the students. The students trying to evaluate the efficacy of the Fizzkeeper, for example, devoted a great deal of time (as well as a large amount of sealant products) to attempting to produce a bottle that would allow them to use the Fizzkeeper while simultaneously measuring the pressure in the head space of the bottle. It appeared that the students with a more applied, rather than theoretical, mindset appreciated the activity.

Student comments on the end-of-semester surveys were mostly positive, and also provide some insight into why students enjoyed the activity. Comments reflected

TABLE 1
Assessment Results for CO_2 Absorption Activity

Aspect Assessed	Fall 2003	Fall 2004
Average response to: "This session improved my understanding of what chemical engineering is and what chemical engineers do."	4.07 (out of 5)	7.23 (out of 10)
Average response to: "This session increased my enthusiasm for studying chemical engineering."	3.64 (out of 5)	7.05 (out of 10)
Number of students listing the CO_2 activity in response to the following: "Of all the activities we did in class, which three did you find the most useful?"	N/A	15 (out of 36 respondents)
Number of students listing the CO_2 activity in response to the following: "Of all the activities we did in class, which three did you enjoy the most?"	N/A	17 (out of 36 respondents)

the following positives about the activity:

1. *Provided an opportunity for a hands-on/laboratory activity*
2. *Allowed students to work in a group*
3. *Gave an idea as to what chemical engineers do*

The opportunity for students to work in groups was particularly well received. This was a great way for freshmen to get to know their colleagues, make friends, and form study groups for introductory science and engineering courses. Students were forced to work in groups to decide what experiments to run, to conduct those experiments, and to write the final report on the project, leading to closer interactions than what usually occur in a lecture course.

A few negative comments were noted. Comments in 2003 indicated that group dynamics were an issue. Some students felt as if they had done all the work while other students had done very little. To address these concerns, the next year more time was spent discussing group work, and peer review of group members was implemented. Another negative comment, noted in both years, was that the project goals were not well defined. This may, in part, be caused by the open-ended nature of how the project was implemented. Student groups were allowed to select their own projects with little input from the instructor. Perhaps more input is needed when the groups are selecting projects to ensure that the topic chosen will yield good results and that the groups properly define their objectives.

CONCLUSIONS

CO₂ absorption in carbonated beverages can be used as a hands-on activity in an introductory chemical engineering course to educate students on chemical engineering. This

activity allows students to investigate a relatively familiar phenomenon, a carbonated beverage going flat, using engineering analysis. The CO₂ absorption activity was successfully implemented in a freshman introductory course at Kansas State University. Students responded positively to its impact on their understanding of and enthusiasm for studying chemical engineering. Most students also listed this activity as one of the most fun and useful activities in the course. Student comments indicated that they valued the hands-on nature of the activity and enjoyed working in groups on a significant “real world” engineering project.

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THE DEVIL'S IN THE DELTA

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As I enter my 40th year of teaching, it seems appropriate to remind teachers and students of a fundamental error that occurs with surprising frequency. This error is particularly evident in courses that cover a wide variety of chemical engineering topics and pull together subjects supposedly learned in previous courses. The senior design course and a chemical engineering laboratory with a variety of experiments fit this type of course. In teaching these courses I have frequently encountered quite bright students who misuse the deltas. Since the differences among the various deltas should be obvious and not at all confusing, it is remarkable that errors of this type crop up so frequently. But they do.

This paper will describe a particularly useful experiment in the undergraduate Lehigh University chemical processing laboratory that uses all three of the deltas and, therefore, helps to cement in the minds of students the fundamental differences among the three kinds.

The title of this paper originates from the old expression “The devil is in the details.” (Some of you may also remember Flip Wilson’s famous portrayal of Miss Geraldene with her expression, “The devil made me do it.”)



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THE DEVIL DELTAS

A brief review might be useful to clarify the issues and applications addressed in this discussion.

“In Minus Out” Delta

An “open” flow process has streams entering and streams leaving. Mass, component, and energy balances can be applied under either steady-state or dynamic conditions. For example, a steady-state energy balance for a distillation column with a single feed and two products is

$$\Delta H = Q - W$$

The delta in this equation is

$$\Delta H = Bh_B + Dh_D - Fh_F$$

where the streams leaving the column are the distillate (with flow rate D and specific enthalpy h_D) and the bottoms (with flow rate B and specific enthalpy h_B), and the stream entering the column is the feed (with flow rate F , and specific enthalpy h_F). Of course, appropriate and consistent units must be used for flow rates and specific enthalpies. If the flow rates are in moles per time, the specific enthalpies must be in energy units per mole (*e.g.*, Joule, kcal, Btu).

In a heat exchanger, streams are heated or cooled. Under steady-state operations with no phase change, a stream enters at temperature T_{in} and leaves at temperature T_{out} . If the mass heat capacity c_p is constant and the mass flow rate is F_M , the ΔH for the stream is

$$\Delta H = F_M c_p (T_{out} - T_{in})$$

If there is a phase change, for example if steam is entering as a vapor with specific enthalpy H_{in} and leaving as liquid condensate with specific enthalpy h_{out} through a steam trap, the ΔH for the steam is

$$\Delta H = F_{steam} (h_{out} - H_{in})$$

In fluid flow systems, the appropriate deltas are differences in pressure, elevation, velocity, and density between the inlet and the exit conditions.

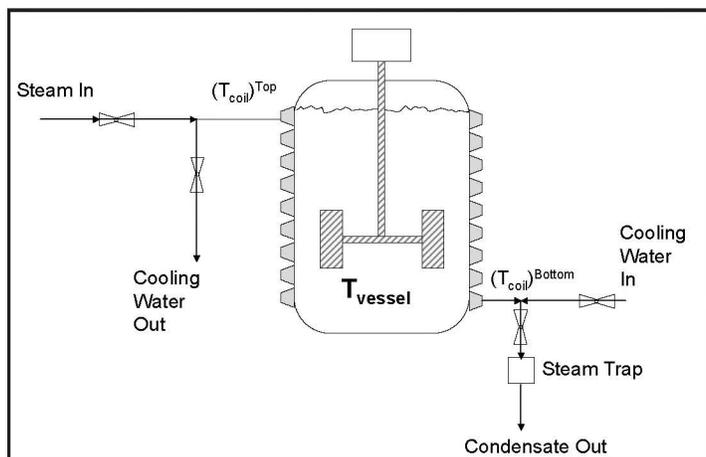


Figure 1. Heated or cooled agitated vessel.

“Driving Force” Delta

Transport processes occur because of differences in driving forces. In heat transfer, the difference is between hot and cold temperatures. In mass transfer, the difference is between large chemical potential and small chemical potential (partial pressure, concentration, or activity). In momentum transfer, the difference is between high pressure or velocity and low pressure or velocity.

For example, consider a perfectly mixed vessel that is surrounded by a jacket. The temperature of the liquid in the vessel is T_{vessel} . Suppose the jacket is completely filled with condensing steam at temperature T_{steam} . The driving force for heat transfer is

$$\Delta T = T_{steam} - T_{vessel}$$

The heat-transfer rate Q that results from the driving force ΔT is

$$Q = UA_H \Delta T = UA_H (T_{steam} - T_{vessel})$$

where U is the overall heat-transfer coefficient and A_H is the heat-transfer area of the vessel wall. In this example, the jacket temperature is the same at all positions in the jacket.

If the vessel is cooled or heated by a fluid flowing through the jacket or through an internal or external coil in plug flow, the temperature of this fluid changes with position. Therefore the temperature driving force changes, and a log-mean temperature difference must be used.

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)}$$

where the two deltas are the temperature differences at the inlet and outlet ends of the jacket or coil.

$$\Delta T_1 = T_{vessel} - T_{Cin}$$

$$\Delta T_2 = T_{vessel} - T_{Cout}$$

Now the heat-transfer rate is

$$Q = UA_H (\Delta T)_{LM} = UA_H \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)}$$

If a circulating cooling water system is used with a high rate of circulation, the temperature in the jacket is essentially constant at some temperature, T_J . The heat-transfer rate is

$$Q = UA_H \Delta T = UA_H (T_{vessel} - T_J)$$

In this type of system, a cold makeup water stream at T_{Cin} is added to the circulating loop, and water is removed at the jacket temperature T_J . A circulating cooling water system has superior dynamics compared to the once-through system. The high circulation rate maintains a high coolant-side film coefficient that does not change

with the load on the system (the makeup water flow rate), so time constants are less variable.

“Time” Delta

The variables in a dynamic process change with time, so we can talk about changes in time, Δt , and changes in properties, Δx , between their value at one point in time and their value at a later point in time. For example, when the liquid in a vessel is heated at startup, the temperature changes with time.

$$\Delta T = T_{(t_2)} - T_{(t_1)}$$

At any point in time the rate of change of temperature is

$$\frac{dT}{dt} \approx \frac{\Delta T}{\Delta t} \approx \frac{T_{(t_2)} - T_{(t_1)}}{t_2 - t_1}$$

if the time increment between t_2 and t_1 is small.

LABORATORY EXPERIMENT USING ALL THREE DELTAS

Apparatus

The process consists of a stirred vessel, 1 m in diameter containing 785 kg of water. The rpm’s of the agitator can be varied to see the effect on the inside film coefficient. A spiral coil is wrapped around the outside of the vessel, making nine wraps around the circumference. Figure 1 gives a sketch of the apparatus. The tank is equipped with a 0.3 m, 6-blade impeller with four baffles. The heat-transfer area is 3.14 m².

The liquid in the vessel is initially at ambient temperature. It is heated by introducing steam at the top of the coil. Condensate leaves at the bottom through a steam trap. Temperatures inside the vessel and at the inlet and outlet of the coil are monitored by a data acquisition system.

When the temperature of the vessel reaches about 90 °C, the steam is shut off and cooling water is introduced. The water enters at the bottom of the coil and leaves at the top.

Data and Analysis

Figure 2 shows typical temperature vs. time trajectories for the batch heating and cooling. The temperature in the coil during heating is shown as being constant at the steam temperature. This is actually not the case because it takes some time for the coil to become completely full of steam. This complicates the analysis of the heating step because the temperature profile along the coil is not known until it is full of steam. We consider this later in this paper.

The analysis of the cooling step is much more straightforward, and our discussion for the purpose of illustrating the “devil deltas” will concentrate on this part of the batch cycle.

The flow rate of cooling water is constant and can be measured by the old-fashioned “bucket and stop watch” method. The inlet and outlet cooling water temperatures are measured, as is the vessel temperature.

At any point in time, there are two ways to estimate the instantaneous heat-transfer rate. From the measurement of the cooling water flow rate and inlet and outlet temperature, the heat-transfer rate at that point in time is

$$Q_{CW} = F_{CW}c_p(T_{C,out} - T_{C,in})$$

This is the “out minus in” delta. At time equal 30 minutes in Figure 2, this “out-minus-in” delta is

$$\Delta T_{out-in} = T_{C,out} - T_{C,in} = 38 - 15 = 23 \text{ }^\circ\text{C}$$

The heat-transfer rate can also be estimated by the time rate of change in vessel temperature. This uses the “time” delta. At time equal t_n , the instantaneous rate of heat transfer to the fluid in the vessel is

$$Q_{vessel(t=t_n)} = M_{vessel}c_p \frac{(T_{vessel})_{(t=t_n)} - (T_{vessel})_{(t=t_{n-1})}}{t_n - t_{n-1}}$$

Since the heat-transfer rate varies with time, the slope of the temperature vs. time curve varies during the batch cooling step. Having two independent ways to estimate the rate of heat transfer improves reliability of the estimated film coefficients. Figure 2 shows this delta at 30 minutes is about 3.5 °C per minute (the slope of the vessel temperature line).

$$\Delta T_{time} = 3.5 \text{ }^\circ\text{C / minute}$$

Using this value, the instantaneous heat-transfer rate is calculated to be 192 kW. The heat-transfer rate from the flow rate of cooling water (2 kg/sec) and the inlet and outlet cooling water temperatures is very close to this number.

The temperature of the cooling water in the coil varies along its length, so a log-mean temperature difference is used. This is the “driving force” delta,

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)}$$

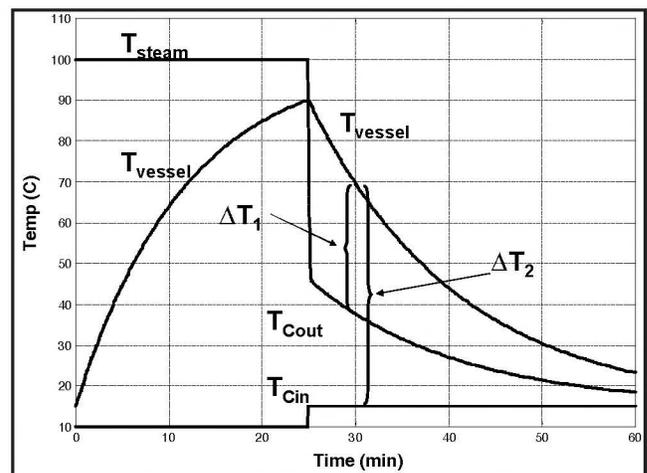


Figure 2. Temperature profiles and temperature deltas during cooling.

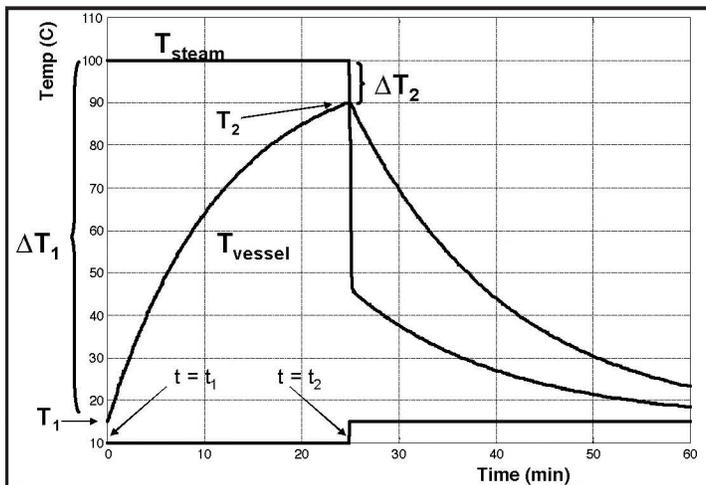


Figure 3. Using time delta for heating phase with constant U and T_{steam} .

where the two deltas are the temperature differences at the inlet and outlet ends of the coil.

$$\begin{aligned}\Delta T_1 &= T_{\text{vessel}} - T_{\text{Cin}} \\ \Delta T_2 &= T_{\text{vessel}} - T_{\text{Cout}}\end{aligned}$$

The log-mean temperature difference at this point in time is

$$\Delta T_{\text{LM}} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} = \frac{(70 - 38) - (70 - 15)}{\ln\left(\frac{70 - 38}{70 - 15}\right)} = 42.5 \text{ }^\circ\text{C}$$

With a heat-transfer area of 3.14 m^2 , the overall heat-transfer coefficient is

$$U = \frac{Q}{A_H \Delta T_{\text{LM}}} = \frac{192}{(3.14)(42.5)} = 1.44 \text{ kWm}^{-2}\text{K}^{-1}$$

The vessel inside film coefficient can then be calculated by accounting for heat conduction through the vessel wall and estimating the film coefficient inside the coil using the Dittus-Boelter equation and an appropriate equivalent diameter.

Even with a constant agitator speed, there is some variation of the overall heat-transfer coefficient and the inside film coefficient with time. This occurs because the varying vessel temperature affects the viscosity of the water.

Approximate Analysis for Heating Step

If the temperature in the coil was constant during the heating period and the overall heat-transfer coefficient was also constant with time, the analysis would be quite simple. It would use “time” deltas in a way that may not be obvious. The situation is analogous to the steady-state flow of fluid down the length of a heated tube. In that situation, the appropriate driving force for calculating the heat-transfer rate is a log-mean temperature difference using the temperature differentials at the inlet and exit ends of the tube. The log-mean temperature difference assumes a constant heat-transfer coefficient. The independent variable is length.

In the batch heating situation, the independent variable is time, but the heat-transfer equations are the same. Therefore, total heat transfer can be calculated by the change in vessel temperature from some point in time to another point in time. The driving force can be calculated using a log-mean temperature difference based on the difference between the constant steam temperature and the temperature of the vessel at the two points in time.

The similarity between length and time coordinates is understood if you visualize a little particle of fluid flowing down the tube in steady-state flow. It sees a constant steam temperature and is heated as it flows along. This is exactly the same as the batch heating of a vessel.

It should be emphasized that the analysis discussed in this section makes two important assumptions. First, the steam temperature is constant. Second, the overall heat-transfer coefficient is constant.

Figure 3 shows how the vessel temperature changes during heating. It starts at T_1 when time is t_1 and ends at T_2 when time is t_2 . The total amount of energy added during this period is

$$\text{Energy} = M_{\text{vessel}} c_p (T_2 - T_1)$$

The average heat-transfer rate over this period is

$$Q = \frac{\text{Energy}}{t_2 - t_1} = \frac{M_{\text{vessel}} c_p (T_2 - T_1)}{t_2 - t_1}$$

The instantaneous energy balance on the fluid in the vessel is

$$M_{\text{vessel}} c_p \frac{dT_{\text{vessel}}}{dt} = A_H U (T_{\text{steam}} - T_{\text{vessel}})$$

This linear ordinary differential equation can be integrated to give

$$T_{\text{vessel}(t)} = T_{\text{steam}} + c_1 e^{-\left(\frac{A_H U}{M_{\text{vessel}} c_p}\right)t}$$

The constant of integration c_1 is evaluated at the initial condition where $T_{\text{vessel}} = T_1$.

$$c_1 = (T_1 - T_{\text{steam}}) e^{\left(\frac{A_H U}{M_{\text{vessel}} c_p}\right)t_1}$$

The time dependent vessel temperature is

$$T_{\text{vessel}(t)} = T_{\text{steam}} + (T_1 - T_{\text{steam}}) e^{-\left(\frac{A_H U}{M_{\text{vessel}} c_p}\right)(t-t_1)}$$

Evaluating this equation at time equal t_2 where $T_{\text{vessel}} = T_2$ gives

$$T_2 = T_{\text{steam}} + (T_1 - T_{\text{steam}}) e^{-\left(\frac{A_H U}{M_{\text{vessel}} c_p}\right)(t_1-t_2)}$$

Rearranging gives

$$\frac{T_2 - T_{\text{steam}}}{T_1 - T_{\text{steam}}} = e^{-\left(\frac{A_H U}{M_{\text{vessel}} c_p}\right)(t_2-t_1)}$$

Taking the natural log of both side of this equation gives

$$\ln \left[\frac{T_{\text{steam}} - T_2}{T_{\text{steam}} - T_1} \right] = - \left(\frac{A_H U}{M_{\text{vessel}} c_p} \right) (t_2 - t_1)$$

Rearranging and substituting the previously defined equation for Q give

$$\ln \left[\frac{T_{\text{steam}} - T_2}{T_{\text{steam}} - T_1} \right] = - \left(\frac{A_H U (T_2 - T_1)}{M_{\text{vessel}} c_p (T_2 - T_1)} \right) (t_2 - t_1)$$

$$\ln \left[\frac{T_{\text{steam}} - T_2}{T_{\text{steam}} - T_1} \right] = \left(\frac{A_H U (T_1 - T_2)}{Q} \right) (t_2 - t_1)$$

$$Q = UA_H \frac{(T_1 - T_2)}{\ln \left[\frac{T_{\text{steam}} - T_2}{T_{\text{steam}} - T_1} \right]} = UA_H \frac{(T_{\text{steam}} - T_2) - (T_{\text{steam}} - T_1)}{\ln \left[\frac{T_{\text{steam}} - T_2}{T_{\text{steam}} - T_1} \right]}$$

$$Q = UA_H (\Delta T)_{\text{LM}}$$

In our experimental apparatus, the temperature through the entire coil is not equal to the steam temperature for about half the heating period. In addition, the change in viscosity due to changes in temperature results in variations in the heat-transfer coefficient. So, the simple analysis described above can only be applied for the period toward the end of the heating step.

During the initial part of the heating step when the temperature of the exit stream from the coil is not equal to the inlet

temperature, the full heat-transfer area is not being used for steam condensation. Thus it is uncertain how to calculate an internal heat-transfer coefficient. One approximate method is to assume that the active heat-transfer area varies linearly with time during this period.

Once the temperature of the exit stream from the coil becomes equal to the inlet temperature, either the approximate method discussed in this section or a rigorous approach can be applied. The rigorous method evaluates the inside film coefficient at each point in time by getting the heat-transfer rate from the rate of change of the vessel temperature, and using the differential temperature driving force of T_{steam} minus T_{vessel} and the full heat-transfer area.

For example, in Figure 2 at time equal 20 minutes, the differential temperature driving force is $100 - 85^\circ\text{C}$ and the slope of the T_{vessel} curve is about 1.3°C per minute.

CONCLUSION

This paper has attempted to provide a clear distinction among the three deltas that are used in chemical engineering. Although they are obvious to the experienced engineer, they are often misapplied by young students.

ACKNOWLEDGMENT

Discussions of this experiment with Kemal Tuzla are gratefully acknowledged. \square

AN INTERNET-BASED DISTRIBUTED LABORATORY *for Interactive ChE Education*

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Practical experimentation that processes real signals is essential to helping students understand theory given in textbooks and giving them skills to deal with real problems successfully. An indispensable part of the chemical engineering curriculum, the experimental class is designed to train all students at the same time and in an effective way for acquiring face-to-face interaction. This conventional approach, however, imposes difficulties on students with time or distance constraints. Moreover, due to both safety and security reasons, access to labs cannot be totally free and is restricted in time to ensure the presence of supervision personnel. Interesting proposals have been made to use the Internet for various educational purposes, including different types of virtual laboratory Web sites,^[1] interactive simulations,^[2] and access to real instruments and test benches through a remote connection.^[3-5] In fact, some implementations of remote monitoring and control through the Internet have already reached

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the teaching laboratories of physics^[6] and electrical engineering.^[7] For chemical engineering laboratories, this capability is now available at University of Tennessee at Chattanooga,^[8] University of Texas at Austin,^[9] and MIT.^[10]

With appropriate planning, teachers and students can run Web-connected experiments on a flexible schedule, which provides educational facilities and opportunities for those students whose schedules might be asynchronous.^[8, 11] Another advantage of such remotely accessible laboratories is that teachers and students at another institution can have access to laboratory facilities without incurring the full cost of developing such resources. Rather than several universities spending money on the same equipment for the same experiments, cooperating universities may each carry out one unique experiment and then form an experiment pool.^[12, 13] Using such highly automated experiments for remote operations can allow a drastic reduction in the amount of personnel time required for those particular experiments. It is reported that online laboratories hold promise of being up to two orders of magnitude cheaper than conventional ones.^[14] Having access to tutorials, pictures, past data files, data processing tools, and graphs tracking the dynamic process variables, these Web pages provide students with sufficient resources that can be viewed simultaneously by all class members.^[10] Such expanded access allows the students and instructors to spend less time communicating the operating procedure and more time investigating the experimental results. Remote learning has evolved into a new model of high quality aimed at engaging students in a distinctive learning technology that helps build a solid foundation.^[9, 15]

Advances in available computer software and interfacing techniques enable remotely operated laboratory experiments to be constructed at relatively low cost.^[16] In this paper, we report on the in-house development of remote control and measurement methods for a chemical engineering laboratory on unit operations, which is offered to undergraduate students at Washington University in St. Louis. A client-server

architecture devoted to instrument management through the Internet is built with Visual Basic and LabTECH programming tools, providing a novel approach in comparison to the Java and LabView software employed in other references.^[8-10] The architecture is described along with the specification and design of a geographically distributed system based on standard commercial components. Used for the required undergraduate process control course, a tracer experiment is restructured to illustrate the connection between physical instruments and the server-client Internet system. The experimental data is archived for subsequent viewing and analysis, and the responses of students to the online experiment are assessed.

SYSTEM ARCHITECTURE

To achieve a standard component distribution system, we adopted Internet technologies that allow portability and independence through different client hardware/software architectures. A standard portable language is instrumental for independence of the application from the client system on which it is executed. An Internet browser can now be considered a standard component of any computer installation. Therefore, our approach will automatically work with any widely available hardware/software environment.

The connection between the server and client program is made by a TCP/IP Winsock socket located within both programs, which functions much like a phone receiver/dialer on each side of the Internet. The server and the clients are connected on the same local area network (LAN) within the laboratory or campus. Remote connections can even be set up between the server and a single user working at home.

TCP/IP defines the physical interconnection, data transfer, and message routing management. It is the typical protocol suite adopted in the standard Internet.^[1] The server sends measurement data to the client the same way the client sends control commands to the server, by creating a string of numbers representing all the commands or measurements and sending them through the TCP/IP socket. Like-

wise, once the client receives the measurement string of numbers and the server receives the control string of numbers, the string is parsed, and each measurement or command within the string is sent to its appropriate subroutine within the client or server code.

A block diagram of the proposed solution is shown in Figure 1. The clients are hosted on a user's personal computer while the server runs on a laboratory computer and manages an automatic control and measurement system that embeds programmable instruments. Both client and server computers run programs that are logically split into two layers. One layer in both client and server sides deals with user

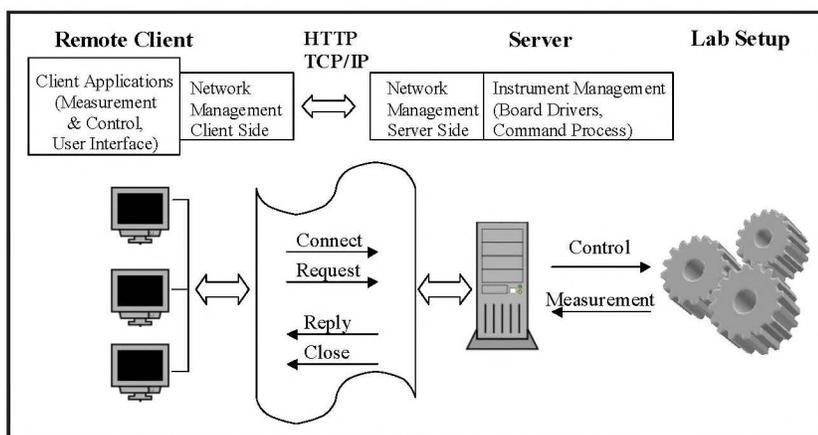


Figure 1. Diagram of the client-server architecture employed to implement the remote control measurement.

[An] advantage of such remotely accessible laboratories is that teachers and students at another institution can have access to laboratory facilities without incurring the full cost of developing such resources.

interface and instrument management, while the other layer deals with network intercommunication. The server is directly connected to the instruments that measure physical quantities. In this work, the server computer, connected physically to the instruments, makes available a set of remotely callable procedures that perform all standard activities (address, read, write, status poll, etc.). The client's command generator issues commands according to the parameter set specified by the user, and sends them via the TCP/IP client socket to the server. The experimental results sent back by the server are then handled and displayed in the client window. The sockets of the client program and the server program are connected by using the server computer's IP address on the Washington University network. The same local port number must be specified within both the client and server sockets. Socket connections and the TCP/IP communication protocols transmit the instrument control commands, parameters, and reports between client and server.

Only one user group is allowed to connect at one time, because physically only one experimental run can be done on the reactor at a time. At the session's termination, the socket connection is closed and the server can accept a new connection on the same port to start a new session. If the client/server connection is broken or remains idle more than five minutes, the server application shuts down the system. If the power shuts down, a system of safety interlocks in the physical system prevents the system from running indefinitely. To protect the server, several techniques can be used, *e.g.*, access restriction based on user identification, firewalls, and encryption. For simplicity and cost reasons, we adopted an approach based on access restriction through user verification of both the password and the IP address of the gateway through which client connects to the server.

On the server site, the structure offers great flexibility. Developed in Visual Basic, the programs require only the addition of a very small number of statements necessary for establishing and closing the interface-related functions of corresponding network functions. When new instruments are added to the instrument library, it is easy to add a measurement or control variable with small modifications to existing programs. The software related to any newly connected equipment can be added to the system without recompiling or modifying the application core. About two or three lines added to the server and client programs will add numbers representing the additional measurement or control variables to the string sent through the TCP/IP socket.

At the client site, because the whole core of the software application (*i.e.*, the components required to share, engage, and release the resources) resides permanently on the server computer, it is not necessary to install any special software tool. Once a new client connection is accepted, the user locally runs the command necessary for selecting and driving an instrument. As a consequence, the proposed structure makes the application portable and safe for remote users.

The server is a Pentium-IV computer with a 1 GHz processor, provided with two independent Universal Serial Bus (USB) ports. The server runs on Windows 2000 Professional and uses drivers from Data Translation to access the Data Translation DT9804 interface board. The server connects to the interface board using a USB cable, and the interface board has analog input/output and digital input/output ports for connection to the physical control hardware of the reactor system. The overall system has been devised to assure reliable communication between the client and the server, and between the server and the physical resources available. A LabTECH ControlPro 12.1 Runtime program receives data and sends commands to the control hardware via the DT9804 interface board. Once the control hardware and server are physically connected to the DT9804 board and the board's drivers are installed, LabTECH can be set up to control the hardware by dragging and dropping control icon blocks from its menu into its workspace.

BUILDING EXPERIMENTAL INSTRUMENTS

The lab setup icon shown in Figure 1 represents any real instrument that requests automatic control and measurement. The proposed server-client system structure can be extended to fit a variety of requirements and serve different experiments. As a test case performed on implementation of the whole system, a tracer study experiment is carried out remotely in real time over the Internet, using a tubular reactor in the Chemical Engineering Laboratory at Washington University. The purpose of the tracer test is to experimentally determine the ideality of a real continuous flow reactor.

In an ideal plug flow reactor, the fluid flows through the reactor with a pistonlike motion and no axial mixing. A real tube reactor, however, cannot reach this ideal state. In the experiment, a conductive tracer was injected into water just before the reactor entrance and the conductivity of the solution mixture was measured at the reactor entrance and exit. The mean residence time, tracer response curve variance, dimensionless variance, and axial dispersion coefficient can

then be calculated. Through data analysis, the tube reactor was compared with an ideal plug reactor.

Figure 2 displays the physical hardware built for the tracer study experiment. The students open the feed flow valve, adjust the water flow rate by varying valve position, start the tracer feed pump, adjust the tracer injection duration, open the tracer injection valve, and then inject the tracer. Air pressure (30-100 psi) is used as the driving force to control the feed flow valve and the tracer injection valve. The feed flow rate is measured by a turbine flow meter downstream, and the measurement is sent to the client application. The conductivity measurement will rise and then fall back to the

steady state value, at which point the students may close the client application.

Table 1 lists all of the process variables used as signals in the tracer experiment. Digital signals are either on or off when equal to 1 or 0, respectively. Analog signals send (Output) or receive (Input) signals within a defined range of values, shown in the "Range" column in Table 1. The output signals control the instrument setup, while the input signals are variable measurements obtained at a specific condition. The types of all variable signals are listed in the "Type" column. The elements that launch and receive signals are listed in the "Origin" and "Destination" column, respectively.

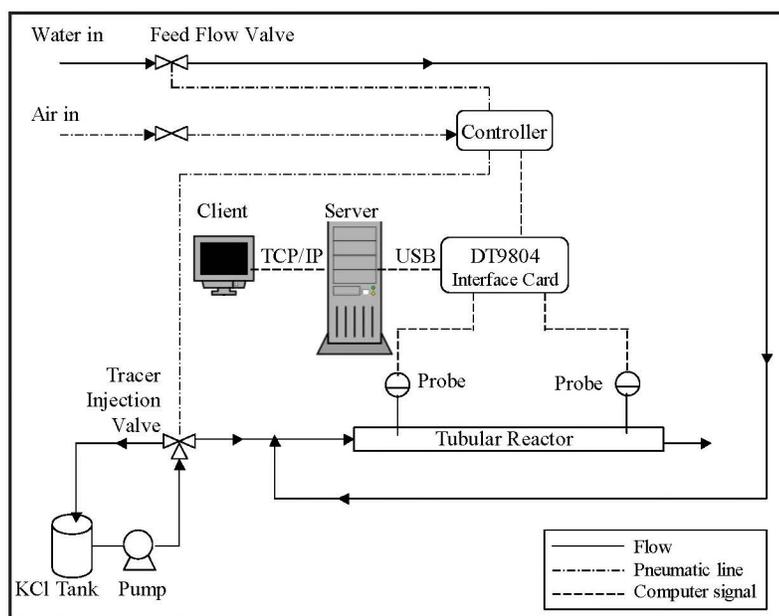


Figure 2. Overview of the physical experimental setup and its connection to the Web.

NETWORKING CREATION FOR ONLINE CONTROL AND MEASUREMENT

The first application in the server computer is the LabTECH Runtime program Traceexe.Itc. It initiates the connection between the physical laboratory setup and the server computer. This connection channel receives measurement signals from the USB port on the interface card and issues commands to control the setup operation. All measurement variables are classified as analog inputs in the Traceexe.Itc program. By specifying the correct interface point, each analog input block in Traceexe.Itc receives the proper signal from the interface card.

The second application in the server computer, Server_TracerStudy.exe, activates the server site and enables it not only to transfer the remote client signal to the physical setup, but also to receive measurements from Traceexe.Itc by continuously using the GetLT function. This function uses a

TABLE 1
Process Variables Used in the Tracer Experiment

Variable	Range	Units	Type	Origin	Destination
Reactor Feed Valve	0-1	Volts	Digital Output	"Client_TracerStudy.exe"	Control Hardware
Tracer Feed Pump	0-1	Volts	Digital Output	"Client_TracerStudy.exe"	Control Hardware
Inject Tracer	0-1	Volts	Digital Output	"Client_TracerStudy.exe"	Control Hardware
Tracer Injection Duration	1-3	sec	Analog Output	"Client_TracerStudy.exe"	"Server_TracerStudy.exe"
Reactor Feed Valve Position	0-100	%	Analog Output	"Client_TracerStudy.exe"	Control Hardware
Run Time	>0	sec	Analog Input	"Traceexe.Itc"	"Client_TracerStudy.exe"
(Reactor) Influent Conductivity	>0	mS	Analog Input	Control Hardware	"Client_TracerStudy.exe"
(Reactor) Effluent Conductivity	>0	mS	Analog Input	Control Hardware	"Client_TracerStudy.exe"
(Reactor) Feed Flow Rate	>0	l/min	Analog Input	Control Hardware	"Client_TracerStudy.exe"

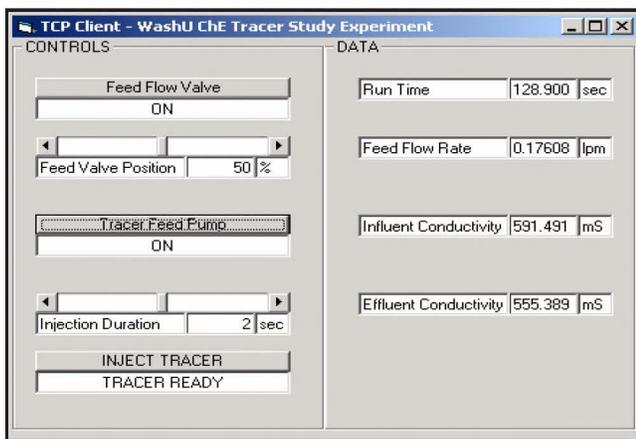


Figure 3. User interface for the client application.

built-in LabTECH application called LT-Speedway to “grab” the analog input data received by Traceexe.ltc. The program Server_TracerStudy.exe takes four measurement variables it receives from its GetLT function and combines them into one string of text, called OutputString. Once the client connects to the server computer using the client program Client_TracerStudy, then Server_TracerStudy.exe sends OutputString across the Internet once every 100 milliseconds to the client program, using a timer within the server program called Timer2.

These two applications must be running before a student can access the experiment using the client program, Client_TracerStudy. The student downloads this program from an Internet page and stores it on the remote computer. Once the student double clicks on the related icon, the client program opens up and connects to Server_TracerStudy on the server. Every command the user manipulates sends text data from the client TCP/IP socket across the Internet to the server TCP/IP socket. The server program sends measurement data acquired from the LabTECH Runtime program Traceexe.ltc back to the client through TCP/IP socket and sends the control variable commands acquired from the client to Traceexe.ltc, where it is executed by that program on the control hardware.

The controlled variables, reactor feed “Valve Position” and tracer “Injection Duration,” are analog outputs in Traceexe.ltc. Before injecting the tracer, the student sets the values of analog outputs by using a scroll bar on the user interface of the client program, Client_TracerStudy.exe, as shown in Figure 3. The student must also open the reactor “Feed Flow Valve,” turn on the “Tracer Feed Pump,” and “Inject Tracer” by pushing the respective buttons on the client user interface. These are digital outputs in Traceexe.ltc. Whenever the student pushes one of the buttons (digital) or slides one of the scroll bars (analog) on the client user interface, the current values of all the digital outputs are combined with the analog outputs as a text string called InputString in the InputData function in the client program. Then InputString is sent to the

server program through the client TCP/IP socket. The server program picks up the InputString of text across the Internet at its TCP/IP socket, separates all of the outputs, and places them in their respective textboxes, as shown on the lefthand side of the image in Figure 4. In the server application, the function PutLT takes each of the values in the textboxes on the lefthand side of the server monitoring window and sends them to their respective input block in Traceexe.ltc. The input blocks receive each signal in Traceexe.ltc and send them to their corresponding Bit Number (digital) or Interface Point (analog) on the DT9804 interface card.

LABORATORY EXPERIENCE

On the project Web site (<<http://it.che.wustl.edu/che473>>), eight groups of undergraduate students have participated in the online operation test. After a class of introduction to the distributed learning technology and two additional classes on the theoretical aspects of the experiment, the instructor demonstrated and monitored experiments using a classroom computer connected to the Internet. When the students were doing the measurements themselves in the computer lab one floor above the laboratory, they were asked to provide their inputs on the user-interface, analyze the experimental outcomes, and answer questions posed by the instructor through interactive dialog. Explanatory Web pages were provided to answer most of their questions on the real instruments during the lab session. As a result of this interactive tutoring mode, students showed more interests in the online operation than the local on-site operation.

During the lab session, students issued commands and parameters from the client window to the server via the TCP/IP client socket. The experimental results were sent back by the server and then handled and displayed in the client window. The client program created a log containing measurements of time, flow rates, influent conductivity, and effluent conductivity. Once the client application is closed, students can open this log to analyze the evolution of the collected tracer

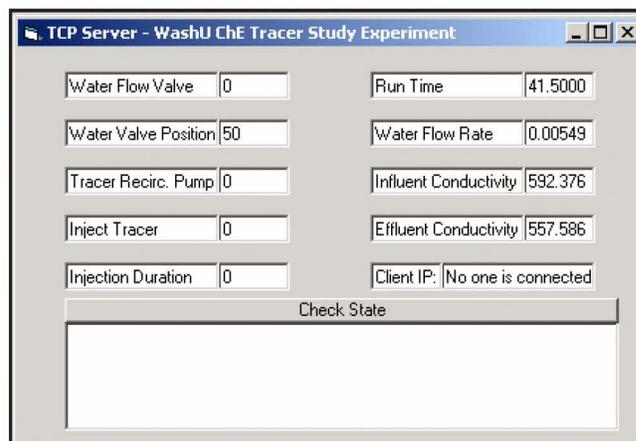


Figure 4. Monitoring window for the server application.

Chemical Engineering Education

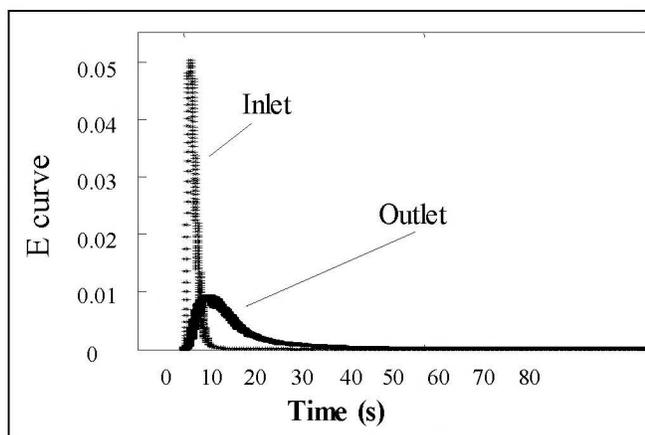


Figure 5. Typical tracer response curves shown in the client side. Measurements are taken at the inlet and outlet of the tubular reactor.

response. Typical tracer response curves at the inlet and outlet with respect to time are shown in Figure 5. In an ideal plug flow reactor, the tracer curves collected at the exit and entrance would be identical as thin, spikelike peaks. This experiment, however, found that dispersion and stagnancy have significant effects on the tracer response curves. The best flow model was determined to be a plug flow reactor with a dead zone to account for the stagnancy, followed by a mixed flow reactor to account for the axial dispersion. The reactor's nonideality must be included in order to predict reactant conversion from given feed rates and reactant compositions.

The experiment was conducted twice, once at a remote client computer station that was Internet-linked to the server, and once at the server computer station directly attached to the setup elements. The typical experimental values obtained from the online remote control and on-site local control, as well as the relative error between these two values, are listed in Table 2. Although there is a time delay between the client and server due to the Web data transfer and the instrumentation synchronization, this delay penalty is negligible when instruments take a long time to complete the measurement.^[4] Hence, the insignificant relative error leads us to conclude that the online control and on-site control give rise to the same

residence time measurement in the tubular reactor.

Student feedback is a key consideration for improvement of the experiment. Surveys were filled out by the students after each lab session to evaluate the beneficial features of the remote learning experience and the fulfillment of educational objectives. The responses contained encouraging comments and constructive suggestions. In general, the proposed survey recommendations were implemented before the next student group was invited to evaluate the lab session. Students agreed that lab sessions became improved with more user-friendly options and tools added to the client window. One feature the students liked most about operating experiments remotely was that it allowed them to perform the process at any time from a place that was convenient for them. The other appreciated feature was that the remote operation helped the students get used to a real world application that was either in a remote control room or at a remote operation facility, especially when hazards and safety concerns were present. Some students showed intention to run the on-site physical experiments as the complimentary reference check since their understanding of the experimental flow scheme can be enhanced with the actual devices in front of them. Actually, this intention could be fulfilled by incorporating the live audio and video streaming to the remote client window so students can listen to the sounds of the device station and view it on the Internet while they are operating. Such sophisticated user interface will soon be added to the current system.

CONCLUSIONS

This paper describes an Internet-based client-server architecture specifically designed to allow flexible management of remote instruments. The proposed solution is portable using the employment of the TCP/IP protocol suite, and also extensible because of the high level of abstraction in system implementation. This approach offers a valuable component to remote engineering instruction that cannot be replaced by simulation software packages. Compared to the traditional way of teaching, due to the absence of schedule and physical constraints, this new approach reaches students who otherwise would not have chance to take these courses and allows a larger and more diversified audience to access

learning opportunities. A set of experiments based on the proposed technique for the control of remote instrumentation has been made available to the students of chemical engineering laboratory courses held in Washington University in St. Louis. There is the opportunity to use this technology to add other experimen-

Valve Opening Position (%)	Actual Flow Rate (cm/sec)	Local Control (sec)	Remote Control (sec)	Relative Error (%)
45	2.93	22.96	23.77	-3.53
55	3.86	18.32	19.02	-3.82
65	5.11	14.57	14.97	-2.75
75	6.02	11.90	12.19	-2.44
85	6.44	11.74	11.38	3.07
95	6.67	10.87	10.67	1.84

tal demonstrations or assignments to one lecture. In order to expand the scope of the experiments and to share costs and software development time, we are planning collaboration on this project with other universities.

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A REALISTIC EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS PROJECT

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The teaching of statistics can be one of the most challenging topics in the engineering curriculum. Students often find the subject matter abstract and the plethora of equations used in analysis rather confusing. For these reasons, an applied approach that emphasizes and reinforces how concepts presented in the statistics course can be used in the practice of engineering has been proposed.^[1] An example is the use of the senior laboratory course to reinforce the concepts presented in the engineering statistics course.^[2] A stronger emphasis on case studies and realistic problems of direct interest to engineering students is also suggested to help motivate and create a more positive attitude toward statistics^[3] and engineering education in general.^[4]

The statistical analysis project described in this article began as a reactor simulation for a senior design course project. It was later integrated into the professional development course, and, after a curriculum revision, the Applied Statistics course, over the last five years. The novel aspects of this project are that the students are given a budget with which to perform

their experimental study, and the experimental results are made available to the students one day after an experiment is requested. Although a process simulation is generating the experimental results, the intent is to mimic a realistic experimental study where results are not available immedi-

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ately and there is an economic limit imposed on the amount of information that can be obtained.

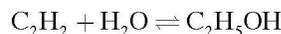
The pedagogical advantage of this approach is it requires students to efficiently plan and adjust their experimental data collection. A similar experimental design philosophy for a gas chromatography experiment is described in Reference 5. It also incorporates student data into the analysis exercise. The integration of data sets collected by students into the teaching of statistics as part of class projects and exercises has been widely advocated. The benefits of this integration are the incorporation of problem-based learning into the statistics course,^[6] and the recognition that experimental data sets represent observations from a larger population distribution, which may yield different “answers” from a statistical analysis.^[7] An important goal of any engineering statistics presentation is the appreciation that a single measurement does not represent the “true” value.^[8]

The approach in this article also avoids the “video game” syndrome that can occur in process simulation exercises. Although simulation modules can be very useful teaching and learning aids in chemical engineering education, they can also impart an exhaustive iteration approach to problem solving and a lack of appreciation for the true time scale of real engineering processes. The addition of a cost and the delay of simulation results in this project are intended to address this issue.

The approach in this article . . . avoids the “video game” syndrome that can occur in process simulation exercises.

EXPERIMENTAL ANALYSIS PROJECT OVERVIEW

In this project, the students determine the kinetic rate constants of both the forward and reverse reaction for the hydrolysis of ethylene to form ethanol.



The hydrolysis is a vapor phase reaction that is catalyzed by phosphoric acid supported on porous solid catalyst pellets. The reaction rate for the hydrolysis can be expressed as

$$R(A) = k_f P_E P_W - k_r P_A \quad (1)$$

in which $R(A)$ is the rate of formation of ethanol ($\text{gmol}/\ell\cdot\text{min}$), k_f is the forward reaction rate constant ($\text{gmol}/\ell\cdot\text{min}\cdot\text{bar}^2$), k_r is the reverse reaction rate constant ($\text{gmol}/\ell\cdot\text{min}\cdot\text{bar}$), and P_E , P_W , P_A are the partial pressures (bar) of ethylene, water, and alcohol.

The students are told that they have a packed-bed tubular reactor available to carry out hydrolysis reaction experiments. They must specify the molar flow rates of the feed components, the outlet reactor pressure, and the average reactor temperature for each experiment. The molar feed rates of the reactants (steam and ethylene) and an inert gas (methane) may be varied by adjusting the corresponding flow controllers. Methane is supplied to the reactor in order to dilute the reacting species and prevent a runaway reaction. The average reactor temperature and reactor outlet pressure can also be varied by adjusting the

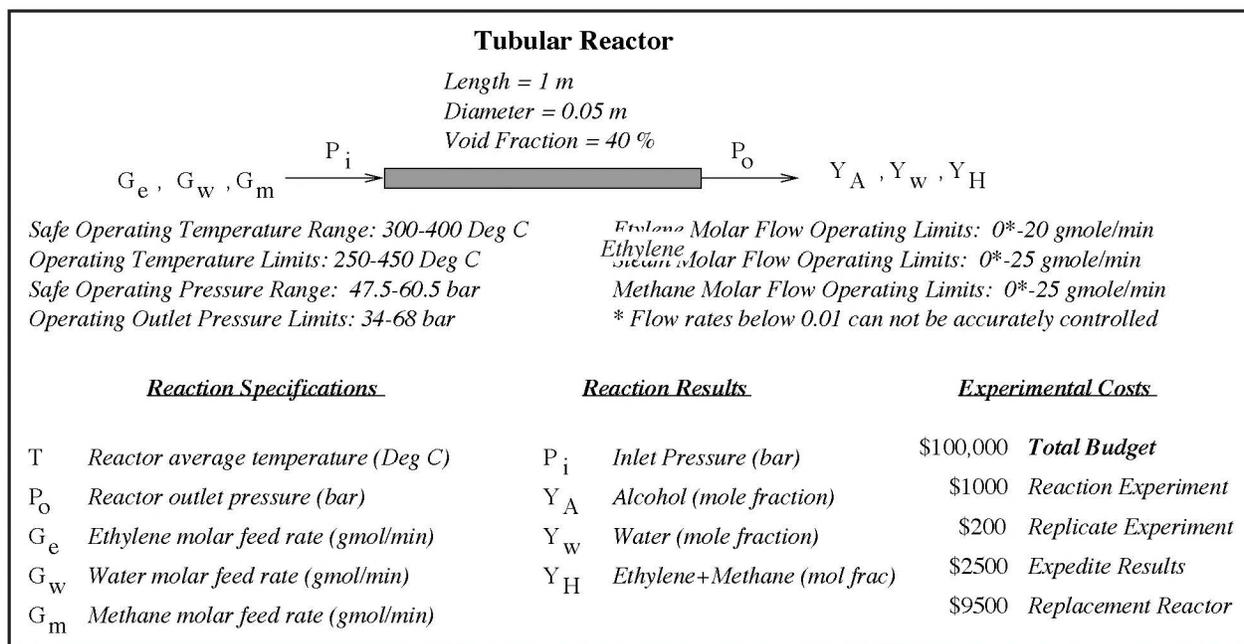


Figure 1. Experimental reactor system.

respective controllers. The reactor outlet gas stream is sampled and analyzed for alcohol fraction and hydrocarbon fraction (ethylene plus methane). Since water cannot be analyzed, it is determined by difference.

The students are given a feasible reactor temperature range of 300 to 400 °C and inlet pressure range of 45 to 65 bar. Under these conditions, the reactor can be safely operated. There is a potential, however, for the reactor to detonate due to an exothermic, runaway reaction at higher temperature or pressure. The students are informed that temperatures beyond 400 °C and inlet pressures beyond 70 bar are dangerous and can very likely result in detonation of the reactor. Operation of the reactor with methane in the feed at the higher temperature and pressure range is also recommended. The students must therefore first determine safe operating conditions from initial experimental trials as discussed in the sequel.

The project is carried out in two- or three-person groups. Each student group is given a \$100,000 budget to carry out the experiments necessary to determine the reaction-rate constants. Each experiment costs \$1,000 for the initial run at a given set of operating conditions and \$200 for each replicate run at the same conditions. The results from each experiment are made available the day after they are requested. An additional \$2,500 cost is incurred in order to receive the results on the same day for each expedited experiment and replicate requested. Experiments can no longer be carried out when there are insufficient funds to cover the cost. If the chosen operating conditions cause the reactor to detonate, the students are charged \$9,500 for a replacement. The intent of this aspect of the project is to illustrate that, as in an actual experimental study, there are consequences to poor experimental design choices. A schematic of the reaction system is presented in Figure 1.

EXPERIMENTAL STUDY

The students are asked to determine the Arrhenius equation parameters, activation energy, and pre-exponential factor for the forward and reverse rate constants. They are also asked to verify that the rate constants follow the Arrhenius equation

$$k = k_0 \exp(-E_a / RT) \quad (2)$$

over the feasible reactor temperature range where k_0 is the pre-exponential factor, E_a is the activation energy, and T is absolute temperature. Both k_0 and E_a can be determined by obtaining each rate constant at two or more temperatures and using the logarithmic transformation of Eq. (2)

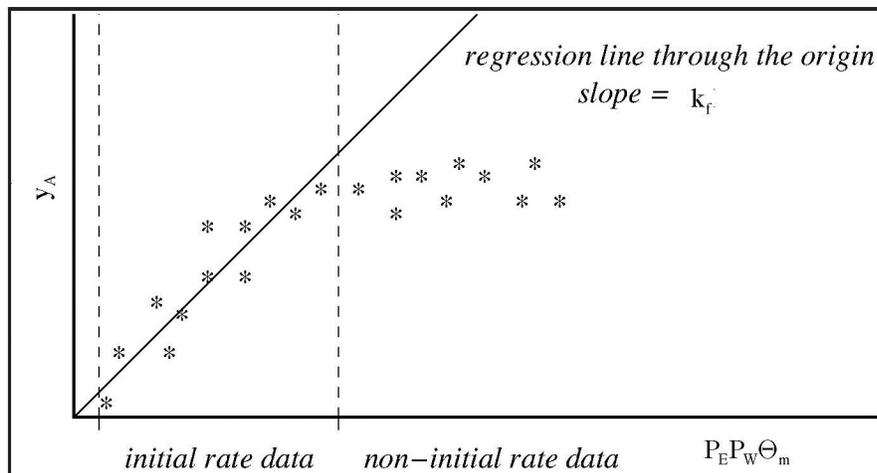


Figure 2. Example initial rate data regression.

$$\ln k = \ln k_0 - \frac{E_a}{R} \frac{1}{T} \quad (3)$$

where $\ln k_0$ is the y-intercept and $-E_a/R$ is the slope of a linear regression of $\ln k$ as a function of $1/T$. In order to determine the forward and reverse rate constants students must carry out two different types of experiments.

Initial Rate Experiments

The initial rate method of measuring reaction rate constants is used to determine the forward reaction rate constant k_f . This technique makes the following assumptions: 1) there is so little product formed that the reverse reaction is negligible; and, 2) the conversion of the reactants is small enough that their concentrations may be taken as constant. Using these initial rate method assumptions with an ideal tubular reactor results in the following relationship for the outlet alcohol mole fraction

$$y_A = k_f P_E P_W \Theta_m \quad (4)$$

where y_A is the mole fraction of alcohol in the exit gas, k_f is the forward reaction rate constant, P_E and P_W are the partial pressures of the reactants, and Θ_m is the molar space time defined as

$$\Theta_m = V / F \quad (5)$$

in which V is the void volume of the reactor and F is the molar feed rate of gas entering the reactor.

Determination of the forward rate constant can be accomplished by noting that y_A is directly proportional to the product $P_E P_W \Theta_m$ in Eq. (4) where the proportionality constant is k_f . A plot of y_A vs. $P_E P_W \Theta_m$ should be a straight line through the origin with slope k_f . When Θ_m increases beyond the value where the initial rate method assumptions are valid, $y_A < k_f P_E P_W \Theta_m$ because the reverse reaction will begin to become significant. Therefore, one would expect the data to begin to deviate from a straight line when the initial rate method assumptions are no longer valid, as illustrated in Figure 2.

A value for the forward rate constant can be determined from the slope of a linear regression on the initial rate experimental data through the origin. The confidence interval on the rate constant is obtained from the confidence interval on the slope of the regression line.

Equilibrium Experiments

If the reactor is operated at low enough feed rates, the reaction will reach equilibrium at the reactor outlet. The equilibrium constant for the reaction can then be determined from these experiments:

$$K_p = \frac{P_A}{P_o P_w} = \frac{y_A}{y_E y_W P_o} = \frac{k_f}{k_r} \quad (6)$$

where P_o is the reactor outlet pressure. The reverse reaction rate constant can be determined once the forward rate constant and the equilibrium constant are known from Eq. (6).

Determination of the equilibrium constant can be accomplished by noting that y_A is directly proportional to the product $y_E y_W P_o$ in Eq. (6), where the proportionality constant is K_p . A plot of y_A vs. $y_E y_W P_o$ should be a straight line with slope K_p . When Θ_m is below the value required for the reaction to reach equilibrium, $y_A < K_p y_E y_W P_o$. Therefore, one would expect the data to deviate from a straight line when the reaction is not at equilibrium, as illustrated in Figure 3.

The equilibrium constant can be determined from the slope of a linear regression on the equilibrium experimental data through the origin. The confidence interval on the equilibrium constant is obtained from the confidence interval on the slope of the regression line. The reverse rate constant is calculated from the ratio of the forward rate constant to the equilibrium constant at a given temperature.

EXPERIMENTAL PROCEDURE

The students are instructed to select at least three temperatures to study. At each temperature, they are encouraged to perform exploratory experiments to determine the feed rate

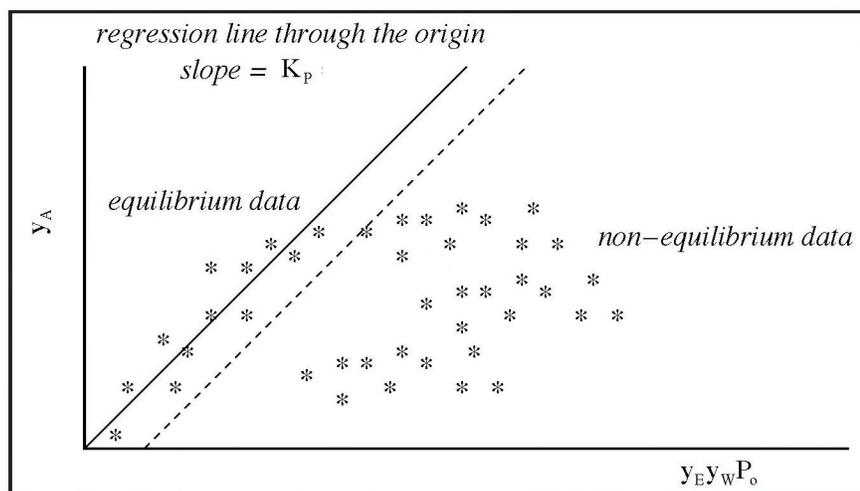


Figure 3. Example equilibrium data regression.

range that will give measurable initial rates and the feed rate range that results in equilibrium. Based on this information, a series of initial rate experiments to determine the forward rate constant and equilibrium experiments to determine the equilibrium constant should be conducted at different feed rates and compositions.

In order to carry out initial rate experiments, the reactor must be operated with high feed rates that result in low outlet alcohol concentration and low consumption of reactants. Although short residence times are necessary for the assumptions made by the initial rate method in Eq. (4) to be valid, the high flow rates will also result in high inlet reactor pressures due to pressure drop across the catalyst packed in the tube. Therefore, students are encouraged to initially obtain an estimate of the pressure drop at high flow rates. Class discussion is used to suggest that this analysis may be safely carried out by operating the reactor without one of the reactants. The low feed rates necessary for the equilibrium assumption in Eq. (6) to be valid can be obtained without similar issues.

Class discussion is also used to point out possible sources of variability in the reaction system study such as error in laboratory analysis and experimental operating conditions. Measuring instruments are often imprecise and/or inaccurate, operating conditions cannot be set precisely as desired, and factors that cannot be observed or controlled can affect the behavior of any system under study. Therefore, any attempt to duplicate or repeat a single set of experimental conditions will usually produce different results. Sometimes the magnitude of this variation is small enough that useful conclusions can be drawn from a single experiment. At other conditions, however, an experiment must be repeated a number of times to be confident that the average value is an acceptable representation of the actual value.

EXPERIMENTAL DATA

The students obtain experimental data by e-mailing the desired reaction conditions for each experiment using a specified procedure outlined in the project description handout. The costs of the experiments are deducted from the student group's budget as they are performed. The results are made available by e-mail to each group member the morning of the following day for normal experiments and by that afternoon for expedited experiments. The results include a summary of the experimental costs and the remaining budget.

A separate e-mail account using the class number as the e-mail address is created each year for this project. Scripts were developed to extract the operating conditions from the e-mail message, pass this

information into the simulation and run it, create a report containing the experimental results and budget information, and then e-mail this report back to the student group. The original intent was to automatically perform each of these tasks without the intervention of the instructor. This approach, however, was quickly abandoned. The ability of undergraduate students to continuously find incorrect permutations to the required e-mail format resulted in increasing complexity to the data extraction script. Keeping in touch with each group's progress and the experiments they requested was also valuable. For these reasons, the project is administered by manual execution of the scripts. The administration task typically takes no more than 10 to 15 minutes each morning. As the report deadline approaches, the time commitment does increase slightly as a larger fraction of student groups request experiments on a given day.

PROCESS SIMULATION

The reactor simulation is performed using the Octave computational environment running under the Debian linux operating system. Octave is a freely available mathematical computation package with similar capability to MATLAB. We note, however, that the Octave program files generated to support this project will not run in MATLAB. Additional information on Octave may be found at the Web site <www.octave.org>.

The reactor is simulated using an isothermal, steady-state, ideal plug flow reactor model. The forward and reverse rate constant activation energy and pre-exponential factor values are modified by the instructor each year. Literature values for these parameters are not used in order to prevent the more industrious student from obtaining the answer and reverse engineering their analysis. The values are also changed each year in order to prevent the less industrious student from getting values out of a prior-year project report. We note that these values are a function of the catalyst system used in the reactor and would be expected to change with different catalysts.

Normally distributed random variation is added to the specified values for reactor operating conditions. A standard deviation of 7.5×10^{-3} mol/min is used for the variation added to each of the requested molar flow rate values and 5×10^{-4} bar is the standard deviation used for the variation added to the requested outlet pressure. There is no variation added to the requested average reactor temperature and the simulation assumes a constant temperature at this value. The pressure drop across the reactor is determined from the expression

$$P_i = P_o + \alpha u^\beta \quad (7)$$

where P_i is the inlet pressure (bar), P_o is the specified outlet pressure (bar), u is the inlet gas velocity (m/min), $\alpha = 1.25 \times 10^{-4}$ and $\beta = 1.25$. These values provide a reasonable pressure drop range for the molar flow rate limits. Slight changes in these values have been made between years. Normally

distributed random variation with a standard deviation on the order of 2×10^{-3} is added to the ethanol mole fraction. The standard deviation of the variation in the hydrocarbon mole fraction is typically half that of the ethanol variation. Slight changes in these values have been made between years. The water mole fraction is determined by different checks made to ensure that reported values are positive and consistent.

Determination of reactor detonation is made by comparing the requested reactor average temperature and computed inlet

The students are informed that temperatures beyond 400 °C and inlet pressures beyond 70 bar are dangerous and can very likely result in detonation of the reactor. . . . The students must therefore first determine safe operating conditions from initial experimental trials

pressure to a table of values. Temperatures below 375 °C or inlet pressures below 70 bar cannot result in detonation. Temperatures above 400 °C require inlet pressures above 69 bar for detonation, temperatures above 390 °C require inlet pressures above 72.5 bar, and so forth. These limits are chosen to make detonation rather difficult unless one is either very careless or intentionally wants to detonate the reactor. There have been few unintentional reactor detonations in our experience with this project. There have been a number of groups, however, who intentionally try to detonate the reactor with their last experiment. Although this practice is not within the scope of presenting a realistic experience to the students, it is not actively discouraged because it does provide a source of amusement and a final goal for some group members.

STATISTICAL ANALYSIS

For each temperature selected, the students are instructed to plot the experimental outlet alcohol mole fraction as a function of P_E/P_W , Θ_m and y_E/y_W , P_i/P_o to determine which data points represent initial rate conditions and which data points represent equilibrium conditions. Deviation from the lines shown in Figures 2 and 3 by a given data point can be caused by experimental variation and/or violation of the assumptions made in the corresponding derivation. Although replicate experimental runs can help quantify the experimental variability, they do not provide the information necessary to exactly determine the point at which the initial rate and equilibrium assumptions are violated. This determination requires some judgment by the students.

A linear regression analysis on the selected initial rate and equilibrium data points is performed using a least squares linear fit through the origin at each temperature studied. The

A number of groups . . . intentionally try to detonate the reactor with their last experiment. Although this practice is not within the scope of presenting a realistic experience to the students, it is not actively discouraged because it does provide a source of amusement and a final goal for some group members.

forward rate constant and equilibrium constant are determined from the slope of the respective lines. A 95% confidence interval on each of these values is determined from the standard error of the slope. These calculations are typically performed by the students using the EXCEL regression data analysis tool. The formulas may also be found in a number of introductory statistics texts. An extensive summary of statistics texts can be found in Reference 8 and is not replicated here.

A value for the reverse rate constant can be obtained from rearranging Eq. (6) to yield $k_r = k_f / K_p$. The determination of a confidence interval, however, is more problematic. The reverse rate constant is the ratio of two independent t-distributed random variables. The result is a Cauchy distributed random variable with an undefined variance.^[9] The unbounded variance arises from the fact that there is a finite probability that the equilibrium constant can be within an arbitrarily small neighborhood of zero. Further discussion of this aspect of the project is presented in the section on discussion topics.

A linear regression analysis based on Eq. (3) can be performed on both the forward and reverse rate constants to determine the activation energy and the log of the pre-exponential factor. This linear regression is also typically performed by students using the EXCEL regression data analysis tool. The students are asked to explain any rate constant values that they believe are inconsistent with the others and excluded from the regression. The activation energy can be determined from the slope using the relationship $E_a = -mR$, where m is the linear regression slope, and a 95% confidence interval can be determined from the confidence interval of the slope by scaling with the gas constant. The pre-exponential factor can be determined from the exponential of the intercept.

The students are asked to determine an estimate of the error variance for the laboratory ethanol analysis from the variance of residuals for each initial rate constant and equilibrium constant linear regression. The result is two error-variance estimates for each temperature studied. They are asked to discuss any differences between the estimated variances and whether the error in the alcohol analysis depends on the amount present in the sample. A 95% confidence interval on the analysis error is determined from the standard error computed from a pooled variance.

REPORTING REQUIREMENTS

Students report their results in a short group memo to the instructor. The memo must contain a description of how the group arrived at their results, and enough detail for someone to replicate their results. An appendix to the memo should contain all of the data that was obtained. Plots of all the initial rate and equilibrium data with the regression line and an indication of which points were used in the regression must be included for each temperature selected. An Arrhenius plot for the forward and reverse rate constants with the regression line and an indication of any rate constant values that were not used in the regression must also be included.

Each group is scheduled for a 10-minute appointment with the instructor where only the instructor and the group members are present. The students turn in the memo, present their results, and answer any questions about their experimental plan and statistical analysis. The intent of this oral presentation is to provide an opportunity for the students to experience a technical interaction with a supervisor that many will encounter early in their careers as practicing engineers.

DISCUSSION TOPICS

The project described in this article brings up a number of topics for discussion concerning the application of the statistical analysis techniques presented in the Ap-

plied Statistics course. The first topic typically brought up in discussion is the method used to determine valid initial rate and equilibrium experimental data. Although many student groups use the “eyeball” method to perform this determination, a more rigorous approach is to perform the regression with and without a given data point and look at the effect on the slope, confidence interval, and correlation coefficient. For points that are questionable, replicate experimental data should be used to help determine whether the deviation is due to experimental error alone.

A second topic for discussion is the basis for the linear regressions used in this project. The students are reminded that the regression equations given in their statistics text, and carried out by EXCEL, assume that there is no error in the independent variable. This assumption is clearly violated in the rate and equilibrium constant regressions due to error in the outlet composition measurements and the Arrhenius expression regression due to error in the average reactor temperature. Although an estimate of the magnitude of independent variable error can be obtained from the ethanol analysis error variance, a formal treatment of linear regression in this case is outside of the scope of the one-semester Applied Statistics course. It is anticipated that student groups would acknowledge that the regression assumption was violated. Very few student groups, however, realize this point without being prompted during the group oral presentation or class discussion. A very valuable contribution from this aspect of the project is to reinforce to the students that they must consider the basis and limitations of a statistics formula before they start performing any calculations.

Some student groups attempt to determine a reverse rate constant confidence interval by dividing the maximum error of the forward and equilibrium constants. A less suspect approach adopted by many student groups is to determine the confidence interval by approximating the variance from the forward rate and equilibrium constant variances as follows

$$s_{k_r}^2 = \left| \frac{\partial k_r}{\partial k_f} \right|^2 s_{k_f}^2 + \left| \frac{\partial k_r}{\partial K_p} \right|^2 s_{K_p}^2 = \frac{1}{K_p^2} s_{k_f}^2 + \frac{k_r^2}{K_p^4} s_{K_p}^2 \quad (8)$$

where the partial derivatives are obtained from the rearrangement of Eq. (6), and $s_{k_f}^2$ and $s_{K_p}^2$ are obtained from the standard error of the slope from corresponding linear regressions. This variance is used to compute the standard error and a confidence interval is obtained from a t-distribution. A confidence interval for the pre-exponential factor is obtained by most student groups from the exponential of the 95% confidence interval of the intercept. Some groups determine the variance of the pre-exponential factor from that of the intercept from

$$s_{k_0}^2 = \left| \frac{\partial \ln(k_0)}{\partial k_0} \right|^2 s_{\ln(k_0)}^2 = \frac{1}{k_0^2} s_{\ln(k_0)}^2 \quad (9)$$

and then compute the standard error and confidence interval using this variance and a t-distribution. These approaches are not correct. Confidence intervals on the reverse rate constant and pre-exponential factor cannot be determined because the parameter variance is undetermined. This aspect of the project attempts to reinforce the concept presented early in the statistics course that nonlinear transformations of normal or t-distributed random variables no longer retain their original distribution. Although it is fair to criticize the practice of asking for values that cannot be computed by the students, they may very well find themselves in this position later in their careers and should have some experience in realizing this point.

A further area of discussion on this topic is how one could obtain a confidence interval for the reverse rate constant and whether there is a more accurate method to determine its value. The students are prompted to consider a revision of the experimental plan that involves performing initial rate experiments using ethanol as the feed. In this case, the reverse rate constant can be determined directly from a single set of experiments in the same manner as the forward rate constant.

STUDENT PERFORMANCE

The student groups are given about five weeks toward the end of the semester to complete this project. They are reminded in class during this period that it takes time to obtain data and they should not wait for the last minute to begin collecting data. Most student groups have successfully determined forward and reverse rate constants for at least three temperatures and have obtained reasonable values for the activation energy and pre-exponential factor. Very few groups have been unable to determine these values. The most typical reasons are the group started their data collection too late in the semester to obtain enough data and/or they were very inefficient in their experimental plan and expended their budget. Grading of the project in these cases is based on their pattern of experimental data requests. Groups that started early and appeared to have a plan but didn't quite get enough good data are treated in a much more forgiving manner than groups that waited for the last minute to request all of their data with little or no planning.

Groups have been formed both by students' own selection and by assignment of the instructor. There have been fewer cases of incomplete or poorly executed projects with the assigned groups, in our experience. Groups are instructed not to discuss any aspect of the assignment with anyone outside of their group, including the exchange of experimental data. Although it is difficult to enforce complete compliance with this policy, analysis of requested experiments has not revealed any obvious signs of copying experimental designs between groups or the use of data that was not requested by a group. We note that no two groups have ever obtained the

same values for the Arrhenius parameters or used exactly the same number of experiments in a given semester. We have not performed this analysis between different semesters.

CONCLUSIONS

The experimental design and statistical analysis project documented in this article has been developed to provide a realistic experience to students. Based on comments contained in course surveys, students have found the project to be interesting and worthwhile. A number of students have made positive comments on the realistic nature of the experience. Although not incorporated into the scope of this project, additional studies—such as an analysis of variance to determine the sources of variability in the experimental data—can be included within the framework discussed in this article. This project has also provided valuable documentation of the students' ability to design, conduct, analyze, and interpret experiments for Criterion 3b of the current ABET criteria.^[10]

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FORCED CONVECTION HEAT TRANSFER IN CIRCULAR PIPES

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Forced convection inside circular pipes under fully developed conditions is one of the main subjects covered in both undergraduate- and graduate-level heat transfer courses. Two types of boundary conditions are usually considered, *i.e.*, constant wall heat flux and constant wall temperature. In engineering calculations, heat transfer correlations are expressed in terms of the Nusselt number and such expressions require the solution of the energy equation given as

$$\rho \hat{C}_p v_z \frac{\partial T}{\partial z} = \frac{k}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \quad (1)$$

in which the velocity distribution under laminar flow conditions is given by

$$v_z = 2 \langle v_z \rangle \left[1 - \left(\frac{r}{R} \right)^2 \right] \quad (2)$$

When the heat flux at the wall is constant, the temperature gradient in the axial direction, $\partial T / \partial z$, is constant. This makes

the solution of Eq. (1) rather simple since the left side is dependent only on r . Integration of Eq. (1) twice yields the Nusselt number equal to $48/11$. This approach is presented in almost all textbooks on heat transfer and/or transport phenomena.

In the case of constant wall temperature, however, the solution of Eq. (1) requires advanced mathematical skills in partial differential equations.^[1] As a result of this mathematical complexity, the value of the Nusselt number is given as 3.66 in textbooks without presenting the analysis. Incropera and



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DeWitt,^[2] for example, stated that:

“... the solution may be obtained by an iterative procedure, which involves making successive approximations to the temperature profile. The resulting profile is not described by a simple algebraic expression, but the resulting Nusselt number may be shown as $Nu = 3.66$.”

The method of Stodola and Vianello^[3,4] is an approximate technique used for a quick estimation of the first eigenvalue. The purpose of this paper is to show students how to apply this technique in the calculation of the Nusselt number for forced convection in a circular pipe when the wall temperature is constant. From my experience in teaching graduate-level Transport Phenomena and Heat Transfer courses, the method is well received by students.

MATHEMATICAL ANALYSIS

Consider the laminar flow of an incompressible Newtonian fluid in a circular pipe of radius R under the action of a pressure gradient. The fluid is at a uniform temperature of T_o for $z < 0$. For $z > 0$, the wall temperature is kept constant at T_w ($T_w > T_o$) and we want to develop a correlation for heat transfer in terms of the Nusselt number under thermally fully developed conditions.

BULK TEMPERATURE GOVERNING EQUATION

As engineers, we are interested in the variation of the bulk (or, mean) fluid temperature, T_b , rather than the local temperature, T . The bulk fluid temperature is defined by

$$T_b = \frac{\int_0^{2\pi} \int_0^R v_z T r \, dr d\theta}{\int_0^{2\pi} \int_0^R v_z r \, dr d\theta} = \frac{1}{\pi R^2 \langle v_z \rangle} \int_0^{2\pi} \int_0^R v_z T r \, dr d\theta \quad (3)$$

Since both v_z and T are independent of θ , Eq. (3) simplifies to

$$T_b = \frac{2}{R^2 \langle v_z \rangle} \int_0^R v_z T r \, dr \quad (4)$$

The governing equation for the bulk temperature can be obtained by multiplying Eq. (1) by $r \, dr$ and integrating from $r = 0$ to $r = R$, *i.e.*,

$$\rho \hat{C}_P \int_0^R v_z \frac{\partial T}{\partial z} r \, dr = k \int_0^R \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) r \, dr \quad (5)$$

Since $v_z \neq v_z(z)$, the integral on the left side of Eq. (5) can be rearranged, with the help of Eq. (3), as

$$\begin{aligned} \rho \hat{C}_P \int_0^R v_z \frac{\partial T}{\partial z} r \, dr &= \rho \hat{C}_P \int_0^R \frac{\partial (v_z T)}{\partial z} r \, dr \\ &= \rho \hat{C}_P \frac{d}{dz} \left(\int_0^R v_z T r \, dr \right) \\ &= \rho \hat{C}_P \left(\frac{R^2 \langle v_z \rangle}{2} \right) \frac{dT_b}{dz} \end{aligned} \quad (6)$$

On the other hand, the integral on the right side of Eq. (5) takes the form

$$k \int_0^R \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) r \, dr = k \left(r \frac{\partial T}{\partial r} \right) \Big|_{r=0}^{r=R} \quad (7)$$

The heat flux at the wall, q_w , is defined by

$$q_w = k \frac{\partial T}{\partial r} \Big|_{r=R} \quad (8)$$

so that Eq. (7) becomes

$$k \int_0^R \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) r \, dr = R q_w \quad (9)$$

Substitution of Eqs. (6) and (9) into Eq. (5) results in the governing equation for the bulk temperature as

$$\frac{dT_b}{dz} = \frac{2 q_w}{\rho \hat{C}_P R \langle v_z \rangle} \quad (10)$$

THERMALLY FULLY DEVELOPED CONDITIONS

The requirement for a thermally fully developed flow is expressed as

$$\frac{\partial}{\partial z} \left(\frac{T - T_b}{T_w - T_b} \right) = 0 \quad (11)$$

Note that the thermally fully developed condition also implies that the local heat transfer coefficient, h , is a constant.

When the wall temperature, T_w , is constant, Eq. (11) reduces to

$$\frac{\partial T}{\partial z} = \left(\frac{T_w - T}{T_w - T_b} \right) \frac{dT_b}{dz} \quad (12)$$

Substitution of Eq. (10) into Eq. (12) results in

$$\frac{\partial T}{\partial z} = \left(\frac{T_w - T}{T_w - T_b} \right) \frac{2 q_w}{\rho \hat{C}_P R \langle v_z \rangle} \quad (13)$$

NUSSELT NUMBER FOR CONSTANT WALL TEMPERATURE

The Nusselt number is defined by

$$Nu = \frac{hD}{k} \quad (14)$$

The heat flux at the wall is also expressed in terms of the Newton's law of cooling as

$$q_w = h(T_w - T_b) \quad (15)$$

so that the Nusselt number takes the form

$$Nu = \frac{[q_w / (T_w - T_b)] 2R}{k} \quad (16)$$

Elimination of the term q_w between Eqs. (13) and (16) leads to

$$\frac{\partial T}{\partial z} = \frac{\text{Nu}(T_w - T)k}{\rho \hat{C}_p R^2 \langle v_z \rangle} \quad (17)$$

Substitution of Eqs. (2) and (17) into Eq. (1) yields

$$2\text{Nu} \left[1 - \left(\frac{r}{R} \right)^2 \right] (T_w - T) = \frac{R^2}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \quad (18)$$

The boundary conditions associated with Eq. (18) are

$$\begin{aligned} \text{at } z = 0 & \quad T = T_o \\ \text{at } r = 0 & \quad \frac{\partial T}{\partial r} = 0 \\ \text{at } r = R & \quad T = T_w \end{aligned} \quad (19)$$

In terms of the following dimensionless quantities

$$\theta = 1 - \frac{T - T_b}{T_w - T_b} = \frac{T_w - T}{T_w - T_b} \quad (20)$$

$$\xi = \frac{r}{R} \quad (21)$$

the governing equation together with the boundary conditions take the form

$$-2\text{Nu}(1 - \xi^2)\theta = \frac{1}{\xi} \frac{d}{d\xi} \left(\xi \frac{d\theta}{d\xi} \right) \quad (22)$$

$$\text{at } \xi = 0 \quad \frac{d\theta}{d\xi} = 0 \quad (23)$$

$$\text{at } \xi = 1 \quad \theta = 0 \quad (24)$$

It should be kept in mind that the dimensionless temperature, θ , is dependent on only the dimensionless radial coordinate, ξ , for the thermally fully developed condition. Eq. (22) can be easily solved for Nu by the method of Stodola and Vianello.

THE METHOD OF STODOLA AND VIANELLO

The method of Stodola and Vianello^[3,4] is a successive approximation technique to estimate the lowest eigenvalue λ_1 in the boundary value problem of the form

$$\frac{d}{dx} \left[p(x) \frac{dy}{dx} \right] = -\lambda w(x)y \quad (25)$$

with appropriate homogeneous boundary conditions at $x = a$ and $x = b$. The procedure is as follows:

1. Assume a trial function for $y_1(x)$ which satisfies the boundary conditions $x = a$ and $x = b$.
2. On the right side of Eq. (25), replace $y(x)$ by $y_1(x)$.
3. Solve the resulting differential equation and express the solution in the form

$$y(x) = \lambda f_1(x) \quad (26)$$

The first approximation to λ_1 , $\lambda_1^{(1)}$, is given by

$$\lambda_1^{(1)} = \frac{\int_a^b w(x) f_1(x) y_1(x) dx}{\int_a^b w(x) [f_1(x)]^2 dx} \quad (27)$$

4. Repeat step (2) with a second trial function $y_2(x)$ defined by

$$y_2(x) = f_1(x) \quad (28)$$

5. Solve the resulting differential equation and express the solution in the form

$$y(x) = \lambda f_2(x) \quad (29)$$

The second approximation to λ_1 , $\lambda_1^{(2)}$, is given by

$$\lambda_1^{(2)} = \frac{\int_a^b w(x) f_2(x) y_2(x) dx}{\int_a^b w(x) [f_2(x)]^2 dx} \quad (30)$$

6. Continue the process until the desired convergence is obtained.

For the problem at hand, comparison of Eq. (22) with Eq. (25) gives

$$y = \theta \quad x = \xi \quad p = \xi \quad \lambda = \text{Nu} \quad w = 2\xi(1 - \xi^2) \quad (31)$$

A reasonable first guess for θ which satisfies the boundary conditions is

$$\theta_1(\xi) = 1 - \xi^2 \quad (32)$$

Substitution of Eq. (32) into the left-side of Eq. (22) gives

$$\frac{d}{d\xi} \left(\xi \frac{d\theta}{d\xi} \right) = -2\text{Nu}(\xi - 2\xi^3 + \xi^5) \quad (33)$$

The solution of Eq. (33) using the boundary conditions given by Eqs. (23) and (24) is

$$\theta = \text{Nu} \underbrace{\left(\frac{11 - 18\xi^2 + 9\xi^4 - 2\xi^6}{36} \right)}_{f_1(\xi)} \quad (34)$$

The first approximation to the Nusselt number is calculated from Eq. (27) as

$$\text{Nu}^{(1)} = \frac{\int_0^1 \xi(1 - \xi^2)^2 f_1(\xi) d\xi}{\int_0^1 \xi(1 - \xi^2) f_1^2(\xi) d\xi} \quad (35)$$

Substitution of $f_1(\xi)$ from Eq. (34) into Eq. (35) and evaluation of the integrals gives

$$\text{Nu}^{(1)} = 3.663 \quad (36)$$

The trial function for the second approximation is

$$\theta_2(\xi) = \frac{11 - 18\xi^2 + 9\xi^4 - 2\xi^6}{36} \quad (37)$$

Substitution of Eq. (37) into the left-side of Eq. (22) gives

$$\frac{d}{d\xi} \left(\xi \frac{d\theta}{d\xi} \right) = -\frac{\text{Nu}}{18} (11\xi - 29\xi^3 + 27\xi^5 - 11\xi^7 + 2\xi^9) \quad (38)$$

The solution of Eq. (38) using the boundary conditions given by Eqs. (23) and (24) is

$$\theta = \text{Nu} \left(\frac{2457 - 4400\xi^2 + 2900\xi^4 - 1200\xi^6 + 275\xi^8 - 32\xi^{10}}{f_2(\xi)} \right) \quad (39)$$

Therefore, the second approximation to the Nusselt number is given by

$$\text{Nu}^{(2)} = \frac{\int_0^1 \xi(1-\xi^2)f_2(\xi)\theta_2(\xi) d\xi}{\int_0^1 \xi(1-\xi^2)f_2^2(\xi) d\xi} \quad (40)$$

Substitution of $f_2(\xi)$ and $\theta_2(\xi)$ from Eqs. (39) and (37), respectively, into Eq. (40) and evaluation of the integrals gives

$$\text{Nu}^{(2)} = 3.657 \quad (41)$$

which is equal to the exact value calculated by Graetz and Nusselt.

The solution of eigenvalue problems by the method of Stodola and Vianello gives accurate results and convergence is very rapid. Although the integrals seem formidable, they can be easily evaluated using engineering calculation software such as MATHEMATICA or MATHCAD. The method is easy to follow and students have no difficulty in understanding the presented material. The transformation of the governing differential equation, Eq. (1), to the form to which the method of Stodola and Vianello is applied, Eq. (18) or Eq. (22), is also very helpful for students in grasping the concept of area averaging and the difference between local and bulk temperatures, as well as their functional dependence on coordinate directions.

NOMENCLATURE

\hat{C}_P	Heat capacity, J/ kg·K
D	Pipe diameter, m
k	Thermal conductivity, W/m·K
Nu	Nusselt number, dimensionless
q_w	Heat flux at the wall, W/m ²
R	Pipe radius, m
r	Radial coordinate, m
T	Temperature, K
T_b	Bulk temperature, K
T_w	Wall temperature, K
v_z	Axial velocity, m/s
$\langle v_z \rangle$	Axial average velocity, m/s
z	Axial coordinate, m

Greek symbols

θ	Dimensionless temperature
ξ	Dimensionless radial coordinate
ρ	Density, kg/ m ³

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Future of Chemical Engineering: **INTEGRATING BIOLOGY INTO THE UNDERGRADUATE CHE CURRICULUM**

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Creating a working knowledge of biological principles in students and developing their ability to apply engineering principles to biological systems (and vice versa) is recognized nationwide as a goal for chemical engineering programs.^[1-5] The same can be said from a global perspective.^[6] There is currently a significant movement to change chemical engineering department names to reflect faculty expertise in bio-focused engineering.^[7] Bioengineering is very broad and inherently interdisciplinary. The need for bioengineers is on the rise. By 2010, there is projected to be a 31.4% increase in employment positions in bioengineering fields.^[8] Moreover, most engineering jobs listed in the “Fast Company 25 Top Jobs” are bio-related.^[9] To meet the needs of the global job market today’s chemical engineering students must receive a solid background in biology. The conventional approach is to add a standard biology course, and many schools do offer biology courses at the senior or graduate level.^[10, 11] The integration of biology in the undergraduate chemical engineering curriculum, however—although difficult in an already overloaded curriculum—provides a more holistic and rewarding learning experience.

Patricia Mosto has extensive environmental science experience. She has been actively involved with field and laboratory projects related to water quality and pollution issues for the last 30 years. She has worked with the Departments of Water and Power and Sanitation in Los Angeles for 10 years. In her 14 years at Rowan, she has supervised more than 50 independent undergraduate projects, taking many students to national and international conferences. She is author of over 100 publications.

Mariano Savelski has seven years of industrial experience in design and manufacturing. He has received a Lindback Foundation Award to continue his research in the area of industrial wastewater minimization, as well as a U.S. EPA Award to investigate zero water discharge cycles in manufacturing and chemical plants. He has been recognized as a rising star in chemical engineering and participated as a panelist in the 2001 Galaxy of Stars at the ASEE meeting in Albuquerque. He has been actively involved in undergraduate research through Rowan Engineering’s clinic.

Gregory B. Hecht has extensive research experience in prokaryotic genetics and molecular biology. With Dr. Mosto, he has developed a new course for chemical engineering students, *Biological Systems and Applications*. He is the creator and coordinator of the Rowan University Student Research Symposium, an annual forum at which Rowan students from all of the SMET disciplines present the results of their independent research.

Stephanie H. Farrell received her B.S. in 1986 from the University of Pennsylvania, her M.S. in 1992 from Stevens Institute of Technology, and her Ph.D. in 1996 from NJIT. Prior to joining Rowan in 1998, she was a faculty member at Louisiana Tech University. Her research expertise is in the field of drug delivery and controlled release, and she is currently focusing efforts on developing laboratory experiments related to membrane separations, biochemical engineering, and biomedical systems for students.

Due to the interdisciplinary nature of the field, this holistic way of teaching integrates both biology and engineering. The biology provides knowledge and skills dealing with biological concepts as the building blocks for engineering design and process. It may also create a whole-system perspective necessary for innovation and creativity. The engineering provides access to existing technologies with an emphasis on the design process itself. At Rowan University, we have developed such an integrated, collaborative approach between engineering and biology faculty to introduce chemical engineering students to the application of engineering principles in biological systems throughout their four-year curriculum. Through specially designed courses and active learning modules that can be easily adapted to any course, students are exposed to the newest biological trends for chemical engineering. The implementation of this philosophy exposes students to key areas of collaboration between biologists and chemical engineers at early stages in their undergraduate education, and continues systematically during the upper years. This strategy develops a cumulative knowledge of biological principles in students, enabling faculty to build increasing detail and technical content into problems and projects that address the interface between biology and engineering. This application allows students to work in interdisciplinary teams, think in a more global fashion, create innovative ideas, and enhance their entrepreneurship and communication skills.

Revisions to the chemical engineering curriculum at Rowan University include: several laboratory modules and projects at the freshman and sophomore levels; a novel, required Biological Systems and Applications course designed to introduce students to a variety of biological principles relevant to chemical engineering^[23]; vertical integration of experiments and applications of bio-related engineering analysis in core engineering courses; collaborative research projects involving biologists and chemical engineers in their junior and senior years; team-taught senior chemical engineering elective courses with strong biological components; and a bioengineering concentration for those graduating with a cadre of bio-related courses.

As the only four-year engineering college in Southern New Jersey, Rowan Engineering is deeply committed to being a major technological resource for the area, preparing students for engineering careers in regionally important industries such as biomedical, biotechnology, pharmaceutical, and food. The abundance of such industry in New Jersey and nationwide creates a steady demand for well prepared engineering graduates. Our collaborative approach to integrating biology and chemical engineering helps prepare students for careers in food, biotechnology, and pharmaceutical industries.

This paper will discuss the implementation, impact, and benefits of our approach, with emphasis on the core courses and junior- and senior-level engineering experiences. A de-

tailed description of the integration of biological principles into the lower levels has been published previously.^[12]

EXPERIENCES AT THE FRESHMAN LEVEL

Generally speaking, the Freshman Clinic sequence corresponds to Introduction to Engineering courses in many other universities, though in unique format. It consists of two parts. In the fall semester we teach basic engineering skills (such as problem solving and teamwork fundamentals) and ethics that will be essential to students' success (or even survival) in engineering school and in their future engineering careers. In the spring semester students are exposed to an intense study of engineering design through reverse engineering (or "dissection") and competitive assessment of consumer products.^[13, 14] Comparable products are reverse engineered to gain understanding of the mechanisms by which they work.

In the Freshman Clinic we immediately establish a hands-on, active-learning environment in which students are introduced to a wide range of engineering principles applied to both biomedical and biochemical systems.^[11, 15-18]

A strategy for introducing biological concepts throughout a traditional engineering curriculum using examples, demonstrations, and experiments has been presented by Maynard and Razatos.^[19] Their approach provides graduating engineers with the skills to handle nontraditional problems and to address emerging areas of research and development. We use a similar approach in integrating biological concepts throughout our core chemical engineering courses at Rowan. An important feature of our implementation method is the emphasis on vertical integration of bio-related course materials and laboratory experiments throughout core courses. Vertical integration enhances educational quality by integrating concepts, skills, models, and data throughout all levels of the curriculum, building upon not only the work done in the previous laboratories of the same course but also those of previous courses. Re-using experiments in freshman, core, and elective courses, as well as in undergraduate research projects, makes efficient use of laboratory equipment and space. This truly integrated learning experience enhances student learning, concept retention, and motivation.^[20-22]

The Freshman Engineering Clinic biomedical engineering project mentioned previously in this paper is used here as an example to illustrate the vertical integration of topics throughout the curriculum. Through eight hands-on modules, students in the freshman course are introduced to a variety of multidisciplinary biomedical topics. Each topic is then explored in greater depth in the appropriate core courses of the chemical engineering curriculum. **Table 1** shows the topical content of the eight hands-on modules taught during the freshman year (first column), with the associated measurements, calculations, and engineering principles (columns 2, 3, and 4). The engineering courses into which the experiments, analysis, and concepts are integrated appear in the right-most

Chemical Engineering Education

TABLE 1
Biomedical Engineering Modules: Measurements, Calculations,
Engineering Principles, and Vertical Integration of Project Modules into Chemical Engineering Courses

	Measurements	Calculations	Engineering Principles	Vertical Integration
Respiration	O ₂ , CO ₂ concentration Air flow rate	Gas volumes Moles of gas Rate of gas consumption and production	Material balances PVT relationships	Mass & Energy Balances Biomedical Processes (elective)
Metabolism	Food intake	Energy expenditure Body surface area	Material balances Energy balances Stoichiometry Correlations Dimensional homogeneity	Mass & Energy Balances Biomedical Processes
Pulmonary System	Lung volume Air pressure Air flow rate Blood O ₂ % saturation	PV work Efficiency Rate of heat transfer Dissolved O ₂ concentration	Mass transfer/separations PV work Efficiency Energy balance Gas solubility/Henry's Law Resistance/Poiseuille's Law	Thermodynamics Mass Energy Balances Fluid Flow Separations Biomedical Processes
Cardiovascular System	Heart rate Blood pressure	Blood flow rate	Mass balance in flow system Fluid flow Bernoulli principle Hydrostatics Pumps—power and efficiency	Fluid Mechanics
Work/Power	Force Distance Recovery time	Work Power Efficiency	Work Energy Power	Dynamics (ME, ECE) Kinesiology (HS)
Mechanics of Materials	For bone and cartilage: Force (tension and compression) Deformation (tension and compression)	Stiffness Dampening	Stress Strain Forces Deformations	Materials Science

column of the table. While the vertical integration of the courses is multidisciplinary and involves other engineering and science disciplines, this table shows only the information that is directly related to the vertical integration into chemical engineering courses.

EXPERIENCES AT THE SOPHOMORE LEVEL

To meet the anticipated growing demand for biology-literate engineers, faculty from biological sciences and chemical engineering worked closely together to develop a lab-intensive course open only to sophomore chemical engineering majors. A detailed description of the Biological Systems and Applications (BS&A) topical content and laboratory exercises has been described previously, along with an assessment of the effectiveness of the course.^[23]

Concurrent with the Biological Systems and Applications course, students take Sophomore Clinic I and II, a multidisciplinary engineering design and practice two-semester

course sequence providing them the necessary technical communication tools. The students work in teams of three to five for the entire semester. The lecture and laboratory sessions are structured so that parallel activities support the eventual completion of the project. In the semesterlong project student teams design and create a microbial fuel cell (MFC) that powers a Lego Mindstorms robot. The design of microbial fuel cells provides an ideal application for many concepts taught in the BS&A course.^[23] In conjunction with the design project, the first semester focuses on total quality management and writing, and the second semester focuses on public speaking.

EXPERIENCES AT THE JUNIOR LEVEL

As part of the clinic sequence at Rowan Engineering, students participate in sponsored research projects during their junior and senior years. Each semester, students work in multidisciplinary teams as part of a two-credit course. Project

funding is provided through either government or industrial grants or sponsorships. Projects span a wide variety of emerging disciplines, depending on faculty expertise and availability of funding. The number of projects that involve integration of biology with chemical engineering has increased dramatically during the seven years the Junior/Senior Clinic has existed. Their preparation during the Biological Systems & Application course allows students to tackle these bio-oriented projects and succeed in their upper-class work.

At the conclusion of four semesters of Junior/Senior Clinic activities, students are expected to:

- *Demonstrate expanded knowledge of the general practices and the profession of engineering through immersion in engineering projects of moderate complexity.*
- *Demonstrate an ability to work effectively in a multidisciplinary team.*
- *Demonstrate acquisition of new technology skills.*
- *Demonstrate understanding of business and entrepreneurial skills.*
- *Demonstrate effective use of project and personnel management techniques.*
- *Integrate engineering professionalism and ethics in their work as it relates to the context of engineering in society.*
- *Demonstrate improved communication skills including written, oral, and multimedia.*
- *Use information obtained from sources that cross geopolitical and language barriers.*

PROJECT 1: BIOETHANOL GENERATION

Currently only 2% of U.S. energy needs are met by renewable resources. The National Renewable Resources Laboratory (NREL), however, projects that biomass resources can eventually provide more than 50% of transportation fuel, reducing dependence on foreign sources of energy, alleviating air pollution problems, and increasing employment opportunities. Bioethanol is one biofuel that has been receiving a great deal of attention in recent years. One factor suppressing wider use of bioethanol is the costs associated with production. In North America, most bioethanol is made from the fermentation of corn. This process sets aside the stalks and leaves of the corn plant referred to as corn stover. It has been estimated that if the corn stover available from current crop yields could be fermented efficiently, bioethanol production in North America could be tripled.^[30] Because of its cellulose and hemicellulose content, however, corn stover is more difficult to ferment than corn itself and is considered to be a waste product of corn farming. In particular, the preparation of the fermentation feedstock and the subsequent increase in ethanol concentrations can be toxic to the fermenting microorganisms. The overall objective of this project is to

create and characterize new strains of the bacterium *Escherichia coli* with the potential to sidestep these issues and, as a result, produce greater yields of ethanol from corn stover. For this project, teams of student researchers are assembled as a cohort of two biology and two chemical engineering majors, and each cohort works with a team of four professors (two from biology and two from chemical engineering). The student cohorts select a particular toxicological problem to investigate over a two-year period. The sum of each cohort's project is broken down into modules with specific objectives that include extensive biological and engineering literature search and review, isolation of novel toxin-resistant derivatives of known ethanologenic microbes, quantification of the toxicological properties of the new strains, pilot fermentation studies to demonstrate the effectiveness of the new strains, and presentations of their results at national microbiology and chemical engineering conferences. This module approach and the cohort composition allows an emphasis on multidisciplinary learning. The experiments conducted by the students address applied microbiology, toxicology, fermentation technology, engineering design, economics, and professional communication. A conscientious effort is made to ensure that all students in the cohort participate in all phases of the experimental design and execution, including determining the effects of altering process variables (*e.g.*, feedstock composition), isolation, and characterization of the biological catalyst with the desired properties, assessing the impact of these activities on the process conditions of the downstream operations and the overall economic feasibility of the system, and disseminating the results at professional venues.

PROJECT 2. ASTAXANTHIN PRODUCTION

Haematococcus pluvialis is one of the largest algal producers of astaxanthin, a carotenoid that is commonly used as a feed supplement in the salmon farming industry to give the salmon their pinkish hue. Astaxanthin is the ideal component to color the salmon because it is a stable natural product and is naturally retained by the fish's flesh. It has already been established^[24] that extreme light conditions yield a higher production of astaxanthin in *H. pluvialis*, however exact light-to-dark time periods for optimum astaxanthin production are unknown. The goal of this project was to determine the proper lighting conditions for optimum astaxanthin production by *H. pluvialis* so a pilot scale plant for large-scale production could be constructed. Two students, one from biology and one from chemical engineering, work over the course of a year with two professors (one from biology and one from chemical engineering). The students grow *H. pluvialis* in an environmental chamber at different light/dark cycles (16/8, 20/4, 24/0) and constant temperature (26 °C) to determine the best light-to-dark ratio for maximum astaxanthin production. Chlorophyll a, ash-dry biomass, and a cell count were obtained daily for each of the growth conditions to establish the optimum growth curves for *H. pluvialis*. Correlations

between growth and astaxanthin production were studied, and a continuous bioreactor for pilot scale production for *H. pluvialis* was designed, constructed, and tested. The 16/8 light-to-dark ratio was used, and it was possible to grow the algae in one compartment and use gravity feed to a separate compartment where the algae were stressed (*e.g.*, longer light cycle, carbon dioxide bubbled into reactor) to enhance astaxanthin production. Several aspects of the reactor were modified for use in Chilean salmon farms in a large-scale algae production facility. This year's Junior/Senior Clinic will complete the design of the reactor.

OTHER PROJECTS

The Junior and Senior Engineering Clinic projects described above are just a few examples of collaborative, multidisciplinary projects that integrate biological and engineering principles. Additional clinic projects have investigated problems related to drug delivery, food preservation, pharmaceutical separations, and artificial organs.

The clinic has proven to be a very effective vehicle for development of educational experiments and course content. The biomedical, drug delivery, and food engineering modules that are integrated throughout the curriculum were developed via the clinic. In a typical project, students would be responsible for collecting background material, building the experimental apparatus, developing the experimental procedure and methods of data analysis, writing a detailed laboratory handout for students, and providing an instructor's manual for a module on a given topic.

EXPERIENCES AT THE SENIOR LEVEL

Food Engineering Course

Rowan Engineering is committed to being a major technological resource for the area, preparing students for engineering careers in regionally important industries such as food processing. The state has major manufacturing operations of top companies such as The Campbell Soup Co., Coca Cola, Anheuser-Busch, General Mills, and Kellogg's. The immediate Vineland area is the hub of Southern New Jersey's food processing industry, home to about 30 companies employing 3,000 people and producing \$700 million in shipments. The abundance of food processing companies in New Jersey demands a steady pipeline of well-prepared engineering graduates. Rowan Engineering students respond to the regional emphasis on food processing with a tremendous interest in the industry. In their senior exit interviews, an overwhelming number of graduating seniors strongly indicated a need for more exposure to food-oriented projects and courses. To respond to student demand and regional industrial needs, chemical engineering faculty have secured support in recent years for undergraduate clinic research projects. Food experiments have been introduced to all engineering students in the Freshman Engineering Clinic (a multidisciplinary,

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introductory course required of all freshmen) and a new Food Engineering elective course was designed for chemical engineering students.

This course provides students with the necessary background in food science, food chemistry, unit operations relevant to food industry (rarely taught in traditional chemical engineering curricula), and finally an approach to food preservation designed and taught by biological science faculty.

Biomedical Engineering Course

The discipline of biomedical engineering has emerged from informal collaborations between engineers, physicians, and life scientists. While relatively new, it is the fastest-growing engineering discipline at most universities.^[20] Chemical engineers play an important and expanding role in this burgeoning field because core chemical engineering concepts are critical to solving medical problems such as the design of artificial organs and drug-delivery devices.

This course introduces students to applications of chemical engineering fundamentals and biomedical systems. Students analyze and design biomedical processes through the application of advanced principles in mass transfer, heat transfer, fluid flow and chemical reactions, pharmacokinetic models, the circulatory system, transport across cell membranes, and human and artificial organs. Several laboratory experiments are conducted to explore the circulatory system, respiration, metabolism, and cardiopulmonary dynamics.

It should be noted that many of the basic biomedical concepts have been vertically integrated throughout the curriculum, beginning with freshman biomedical modules re-introduced in relevant core courses. The specific focus of this course permits these topics and experiments to be explored in greater depth with a more significant emphasis on the associated physiology and other biological concepts.

Drug Delivery Course

Controlled-release systems are designed to provide delivery of a biologically active agent (*e.g.*, a drug or pesticide) at a predetermined rate for an extended period of time. Controlled release offers several advantages over traditional methods of formulation and administration such as: maintenance of effective concentrations for a sustained period, less total agent required, cost effectiveness, convenience, and compliance. This course on controlled-release systems introduces students to chemical engineering fundamentals applied in controlled-release systems. Basic principles of materials, mass transfer, heat transfer, fluid flow, and chemical reactions are used to analyze and design controlled-release systems. Applications to pharmaceutical, agricultural, and food industries are explored, with a primary focus on drug delivery systems. Several laboratory experiments are conducted to explore drug stability, membrane-based transdermal patches, controlled-release tablets, erodible and dissolution-based systems, and osmotic pumps.^[26] Drug delivery topics represent another example of

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vertical integration of experiments and examples throughout the curriculum. Freshmen are first introduced to drug delivery in the freshman year, and drug delivery examples are revisited in core courses such as Transport Phenomena and Mass Transfer. In the senior-level elective on controlled release, students explore drug delivery systems in greater depth, with more emphasis on topics such as distinguishing rate-controlling mechanisms and pharmacokinetic considerations.

IMPACT IN THE CURRICULUM

The combination of modules at the freshman and sophomore level, the Biological Systems and Applications course specifically designed for chemical engineers, the research projects as part of junior and senior clinics, the elective senior courses in Food Engineering, Biomedical Engineering and Drug Delivery, and the Concentration in Bioengineering all help prepare students for a future career in research and industry. Located in Southern New Jersey, Rowan University, through its Junior/Senior Clinic, has successfully completed a wide range of projects generated and sponsored by local industries and agencies. These include private companies (*e.g.*, Biothane, US Filter, Lockheed Martin, Johnson Matthey, General Mills, ExxonMobil) and research foundations (*e.g.*, Engineering Information Foundation, Water Environment Research Foundation). These industrial partnerships benefit both the faculty and the students.^[27] Students are more likely to obtain internships as a result of these experiences, and engineering faculty with expertise that reflects this bio-intensive regional interest strengthen their industry interactions and receive research support. This research interest is reflected in the types of clinic projects offered in the Junior/Senior Clinic

course, such as bioethanol production, astaxanthin production, drug delivery, and food engineering. Working cooperatively with local industry has also enabled students to obtain valuable entrepreneurship experience in supporting small- and medium-size businesses. As part of clinic projects, students may propose their own ideas and gain funding through the National Collegiate Inventors and Innovators Alliance (NCIIA) Venture Capital Fund. This fund is managed by a faculty member and specifically earmarked for the development of original inventions by multidisciplinary student teams within the Junior and Senior Clinics.^[28]

Students often cite a potential career in biochemical engineering as a motivator for pursuing a chemical engineering degree. This interest in the interplay between biology and engineering is apparent in the demand by students for bio-oriented research projects at the junior and senior levels. One measure of student interest in bio-related projects is their participation in Rowan University's student symposium in the Science, Technology, Engineering, and Math (STEM) Symposium. As shown in Figure 1, the percentage of bio-related engineering projects that have been presented at the symposium has increased dramatically. In 1998, only one engineering abstract at the symposium had biology content. By 2004, the number of posters with engineering students pursuing biology-related projects was similar to the number of nonbiology engineering posters. Importantly, Figure 1 demonstrates that 2004 was not a peak but the realization of a new status quo, since subsequent years have had similar numbers of bioengineering presentations. In many cases, the lab component of the BS&A course has directly benefited students working on research projects at Rowan University.

As the beginning cadre of students who have been exposed to these innovations in the curriculum progresses, we expect to develop new engineering courses on molecular biotechnology or bioengineering that will be part of the new bioengineering concentration approved this year within the College of Engineering.

Preparing students early in their college career through a specially designed course and bio-related modules during their Freshman and Sophomore Clinics yields excellent results on their bioengineering clinic project and courses in their junior and senior year. Additionally, students are able to learn more material and applications in the time that is traditionally spent in an introduction to biological principles. Also, the Junior/Senior Clinics fostered a strong research environment, evidenced by the percentage of students pursuing graduate degrees as shown in Figure 2.^[29]

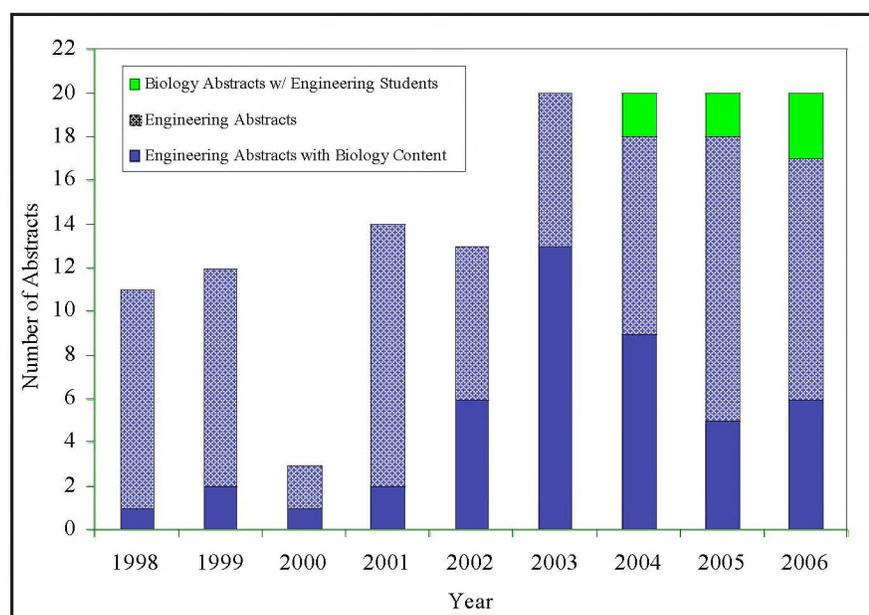


Figure 1. Number of bio-oriented abstracts and total abstracts submitted by engineering students at Rowan University's STEM Symposium.

The impact of the clinic model has been very positive in fostering a spirit of inquiry and engaging students in cutting-edge research as undergraduates.

As a final measure of impact on students, career paths of chemical engineering graduates are considered. The AIChE Placement Survey for Recent Graduates from domestic institutions indicates that 22.5% of chemical engineering graduates found work in biotechnology, pharmaceutical, and food industries. A survey of Rowan Chemical Engineering graduates reveals that more than 27% of chemical engineering graduates found employment in these industries.

SUCCESSFUL IMPLEMENTATION

The implementation of these innovations into the curriculum was relatively smooth, particularly considering that it has required cooperation across not just separate departments but also separate colleges within the university. We believe that several factors were crucial to this success.

Foremost, the culture on the Rowan campus during the implementation process was focused on de-emphasizing the protection of "turf" by the academic departments and moving towards interdisciplinary activity. Importantly, relations between the Departments of Chemical Engineering and Biological Sciences were collegial at the start of the implementation, as were the interactions between the deans of the College of Engineering and the College of Liberal Arts and Sciences. Moreover, both the engineering and the biology personnel viewed the curricular development as a mutually beneficial process. While the curricular development described here has had an obvious benefit for the chemical engineering department, it has also resulted in dividends for the Department of Biological Sciences. No less than four biology faculty have been involved in numerous collaborative research projects, some of which received external funding. Even better, the addition of biology to the curriculum has provided additional research opportunities for biology majors.

Incremental implementation was also important. Incorporation of biological content and application into the curriculum required resources from both departments, which to some degree necessitated a stepwise approach. Initial steps involved the establishment of biology projects in the Freshman and Sophomore Clinics and the creation of the sophomore Biological Systems & Applications course. Subsequent changes in the curriculum at the junior and senior levels would not have been successful without the prior addition of both content and experiential knowledge at the lower levels.

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The future of chemical engineering is in nano- and biotechnology. This curriculum, with its integrative biological components, is at the front of future education.

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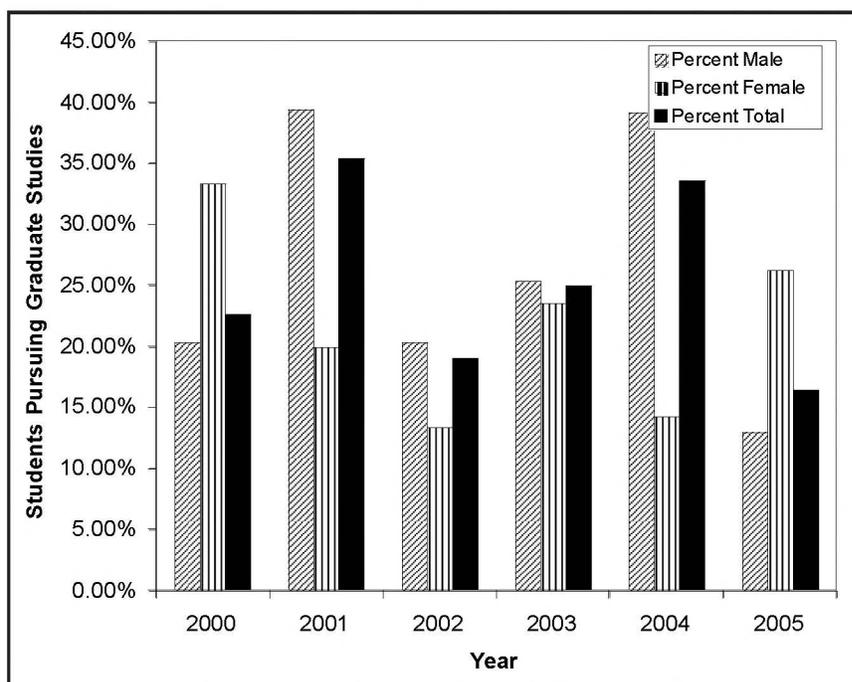


Figure 2. Percentage of students pursuing graduate degrees.^[28]

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Random Thoughts . . .

TURNING NEW FACULTY MEMBERS INTO QUICK STARTERS

REBECCA BRENT
Education Designs, Inc.

RICHARD M. FELDER
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If you're like most faculty members, you began your academic career knowing very little about what you'd be doing for a living. You knew about working on a research project someone else had defined and gotten funded, but not about starting and managing a research program, planning and delivering courses, and dealing with the hundreds of technical and management problems that always crop up in research and teaching. No one told you much about those things after you showed up either, so you had to figure it all out yourself by trial-and-error.

This bizarre approach to career development has unfortunate consequences. Roughly 95% of new faculty members take an average of four to five years to meet or exceed their institution's expectations for research and teaching.^[1, 2] The remaining 5%, however—the ones Robert Boice^[1] calls “quick starters”—manage to do it in their first two years. Considering the enormous investment institutions make in each faculty member they hire, moving more of the new ones into the quick starter category would clearly be good for everyone—the new faculty, their institutions, and the students they will teach and mentor.

Converting new faculty members into quick starters is not impossible—it's not even difficult. You just give them early guidance on how to teach well, do good research, and balance the competing demands of teaching, research, service, and personal life, and supplement this orientation with one-on-one mentoring by skilled senior colleagues.

A program containing those elements has been in place since 2000 in the N.C. State University College of Engineering. We offer it as an example of what can be done—and in our opinion, what should be done—to help new engineering faculty make the transition to their new careers quickly and successfully. In this column, we briefly outline the program (Brent, *et al.*^[3] provide more details) and summarize the lessons we have learned from our experience with it.

Winter 2007

THE NCSU NEW-FACULTY SUPPORT PROGRAM

The centerpiece of the NCSU program is a four-day orientation workshop held in mid-August. It covers grantsmanship, recruiting and working with graduate students, designing courses and getting them off to a good start, effective lecturing and active learning, advising, time management, and dealing with a variety of crises faculty members commonly encounter. All presentations are highly interactive, and the presenters include some of the best teachers and researchers on the faculty as well as key administrators and support staff. The workshop was first given in 2000 to new engineering faculty, and since 2001 it has been given jointly to new faculty in the Colleges of Engineering and Physical and Mathematical Sciences.

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The orientation workshop is followed by a series of hour-long sessions during the academic year that reinforce workshop material and help maintain a sense of community among the participants. Topics addressed include troubleshooting teaching, dealing with funding agencies, and writing effective proposals for CAREER Awards. (Workshop alumni have an excellent record of landing them.) Another component of the support program is mentoring. In 2000, all departments identified specific ways the department heads and senior faculty would provide support to their new hires, and formal mentoring programs have been initiated in several departments.^[3]

The response of the new faculty has been overwhelmingly positive. The participants to date have given the orientation workshop 99 overall ratings of “excellent,” 12 “good,” and no “average,” “fair,” or “poor” ratings. Past workshop participants have given significantly higher ratings than nonparticipants to their career orientations, and preliminary assessments indicate that they have outperformed the nonparticipants in terms of both funded research activity and teaching evaluations. The program has maintained a high level of administrative support and has become a strong selling point for recruiting new faculty.

RECOMMENDATIONS

We have the following suggestions for schools planning their own new-faculty support programs.

- *Keep the program at the school/college level rather than making it campus-wide.*

Many universities have teaching centers that provide new faculty orientation, but since the organizers have to address faculty in all disciplines, they generally limit the program content to such things as campus resources and employee benefits. As important as those topics may be, such programs don't do much to convert new faculty into quick starters. When orientation is designed specifically for faculty in engineering and related disciplines, presenters can use research and teaching examples that are clearly relevant to the participants—and the greater the perceived relevance of presented material, the greater its likely impact on the recipients.

- *Get strong and visible support from the dean and department heads.*

If the director of a teaching center or the associate dean for academics invites new faculty members to attend a four-day workshop two weeks before the start of their first semester, few are likely to show up, while if the dean and department heads strongly encourage attendance and share positive evaluations from past workshop participants, most new faculty will attend.

- *Provide guidance on both research and teaching and discuss how to balance them.*

Most new faculty are nervous about meeting expectations for research productivity. Providing guidance on how to do it is an excellent way to persuade them that the workshop is worth their time. Presenters should also emphasize strategies for making teaching efficient as well as effective and for maintaining a balance of teaching, research, service, and personal life consistent with the institution's expectations and the faculty members' health and sanity.

- *Keep the presentations practical and interactive.*

A workshop that is mainly a parade of talking heads is generally not worth the time it takes to prepare and present it. If a designated presenter doesn't know how to design and deliver an effective interactive presentation, someone else who does should provide some coaching.

- *Treat the participants well.*

The new faculty should feel welcomed into the academic community, and treating them well is one way to make that happen. Hold the workshop in a convenient, comfortable location and don't skimp on the budget for meals and breaks. Provide useful resources in a well-organized notebook. Post lists of good local restaurants, parks and playgrounds, cultural attractions, and automobile repair shops. End the workshop with a celebratory reception and invite all the department heads and mentors to attend and interact with the participants. Make sure mentoring in teaching and research is provided by skilled and supportive colleagues who know something about how to mentor.^[4]

In summary, if the goal is to convert new faculty members into quick starters—productive in research and effective in teaching in their first two years—and the orientation that most of us got (*i.e.*, none) is all that's provided, there is a one-in-twenty chance of succeeding. The strategies we've proposed should improve the odds considerably.

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http://www.ncsu.edu/effective_teaching and at <http://che.ufl.edu/~cee/>

INCORPORATING SIX SIGMA METHODOLOGY TRAINING *into Chemical Engineering Education*

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Six Sigma is a buzz term in today's technology and business worlds. In organizations like Motorola, GE, DuPont, 3M, IBM, Dow Chemical, and PPG, Six Sigma means a measure of quality that strives for perfection.^[1] Statistically, it means reducing the process variation so that \pm six standard deviations lie between the mean and the nearest specification limit. Under the Six Sigma control, the defect probability is 3.4 per million.^[1,2] Six Sigma methodology has been successfully applied to manufacturing (especially chemical and related manufacturing), to research and development, and to business and financial services.

Six Sigma methodology combines elements from several quality movements with advanced statistical methodology. It is a comprehensive tool combining business concepts with technical and leadership skills, and thus it is suitable for professionals at all levels: managers, engineers, and scientists. Recently, there has been great interest in initiating Six Sigma training in college education. This paper reports the success of incorporating Six Sigma methodology into a traditional chemical engineering course, Engineering Experimentation, at Texas Tech University.

CHE 3343/4372, Engineering Experimentation, is a traditional undergraduate elective course in the chemical engineering curriculum at Texas Tech University. The original catalog listing is "strategy in experimentation; planning efficient experiments; analysis of data, interpretation, and presentation results." The course provided an excellent opportunity to incorporate Six Sigma methodology training into traditional engineering education. In practice, the instructor starts the course with an introduction of the fundamentals of Six Sigma methodology, emphasizing the D.M.A.I.C. process that refers



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to Define (D), Measure (M), Analyze (A), Improve (I), and Control (C).^[3] The course is then organized to discuss various methodologies and tools in each process stage. For example, moving range chart/individual chart and range chart/X-bar chart are heavily emphasized to evaluate measurement systems in the process stage of *Measure* (M). The tools in the process stage of *Analyze* (A) overlap with various classical topics in Engineering Experimentation, including: design of experiments (DOE) and analysis (focused on two-level full, half, and highly fractionated factorial designs and analyses), residual and model adequacy analyses, regression model, and confidence levels. Apart from technical content, it is worthwhile to note that a small fraction of Six Sigma management and business concepts are also addressed, mainly in the Define stage. For example, we have discussed a S.M.A.R.T. goal (refers to a goal that is specific, measurable, agreed upon, realistic, and time bounded), thought map (a road map that is composed of different paths of questions), Six Sigma team development, and effective meeting management. A summary of the different topics discussed in each stage of the course is shown in Figure 1. As a more specific example, the instructor included a request to write a S.M.A.R.T. goal for this course in the first homework assignment. The students, working in a group format, answer questions about the course including: what is to be accomplished (S, specific), what level of improvement is needed (M, measurable), what do we agree upon as a team (A, agreed upon), whether the goal can be accomplished by the given available resources (R, realistic), and what the expected dates for major milestones are (T, time bounded). The full D.M.A.I.C. process is then practiced through a formal Catapult Project, discussed later, accounting for 15% of the final grade.

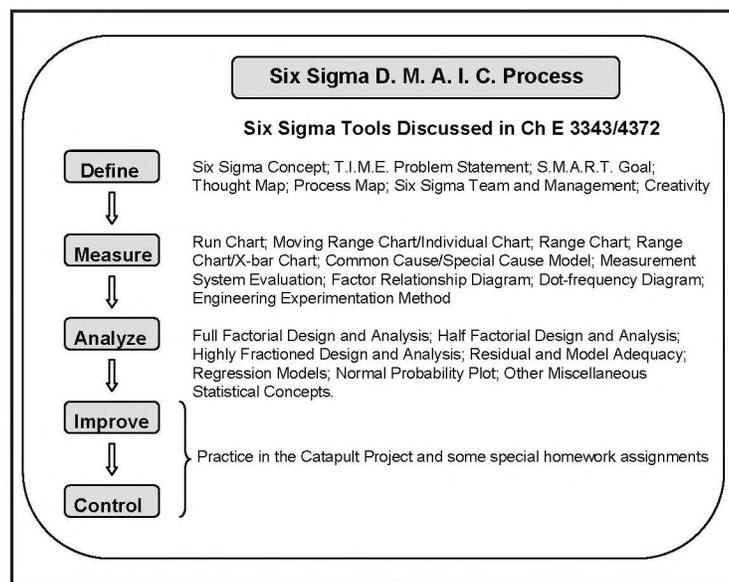


Figure 1. The Six Sigma D.M.A.I.C. process and different tools discussed in CHE 3343/4372.

SPECIAL HOMEWORK ASSIGNMENTS

The homework assignments in CHE 3343/4372 include the problems in the textbook *Design and Analysis of Experiments*^[4] and special problems generated by the instructor. For example, the instructor provided raw data of several projects in CHE 4232, Unit Operations Laboratory (permitted by the class and the instructor Professor T. Wiesner), and requested students perform new analyses using the tools learned in CHE 3343/4372. Such assignments give students opportunities to work on practical problems related to other chemical engineering subjects and, more importantly, allow them to practice the Six Sigma methodology by solving practical chemical engineering problems. In addition, the instructor typically has several nontraditional homework assignments, such as a card-drop exercise related to variation and creativity, a paper airplane mini-project using a 2² full-factorial design to study the influence of airplane weight and launching angle on landing distance, and another card-drop exercise to conduct a 2³ full-factorial design to study the influence of card weight, surface area, and releasing height on target landing.

THE CATAPULT PROJECT

“Tell me, I’ll forget; show me, I’ll remember; involve me, I will understand.”^[5, 6] Without doubt, designing and practicing are the heart of engineering majors. This is an important element in CHE 3343/4372, Engineering Experimentation. A formal Catapult Project assignment, which includes an individual project report, a group presentation, and a group competition, has been assigned for the last four successive years and counts 15% toward the total grade. Catapults are used by more than 200 companies as a training aid in Six Sigma methodology training. A snapshot of the catapult used in CHE 3343/4372 is shown in Figure 2. The project includes four major elements. First, the students are assigned to work in project teams (three to four students per team) to investigate the performance of their catapults including evaluating the measurement system and performing factorial experiments to determine the major influencing factor(s). Second, each student works independently to analyze the collected raw experimental data and submit a formal individual project report. Third, the project team regathers and finalizes the developed model for performance prediction and makes a formal project presentation to the entire class. Lastly, the team will use its developed model for a project competition. During the project competition, the instructor will place the target at a random location within a defined target area and each team needs to launch the ball within three minutes with the goal of hitting the target. Figure 3a shows a brief map of the setup in the project competition and Figure 3b is a snapshot of a ball approaching the target in a 2004 class competition.

The Catapult Project has given the students a unique opportunity to practice the Six Sigma D.M.A.I.C. *Chemical Engineering Education*



Figure 2. A sample catapult.

process. In the Define stage, the students practice various concepts taught in class such as defining a S.M.A.R.T. goal, organizing a thought map, and managing a project team. During the stages of Measure and Analyze, the students evaluate the measurement system and perform two-level full, half, and/or highly fractionated factorial design experiments and analyses to determine the major influencing factor(s). In addition, they will develop a regression model^[4] quantitatively relating the distance as a function of setting parameters such as launching angle, type of ball, rubber band position, and stop pin position. An example of a regression model developed from a 2³ full factorial design is:

$$\begin{aligned} \text{Distance} = & \beta_0 + \beta_1(\text{parameter 1}) + \beta_2(\text{parameter 2}) + \\ & \beta_3(\text{parameter 3}) + \beta_{12}(\text{parameter 1} \times \text{parameter 2}) + \\ & \beta_{13}(\text{parameter 1} \times \text{parameter 3}) + \beta_{23}(\text{parameter 2} \times \\ & \text{parameter 3}) + \beta_{123}(\text{parameter 1} \times \text{parameter 2} \times \\ & \text{parameter 3}) + \text{error} \end{aligned} \quad (1)$$

where β_0 is the average response from the design and β_1 , β_{ij} , and β_{ijk} are calculated from the main effects of single parameters, two-way interactions, and three-way interactions, respectively. Eq. (1) is the regression model that involves all parameters and interactions in a 2³ full-factorial design. For practicality, the students have choices of including only significant factors. The model adequacy will be evaluated by various residue analyses. Finally, the students move to the Improve and Control stage to optimize and apply the developed regression model. For example, during the project competition, each project team will measure the distance where the instructor randomly locates the target (within the target area) and use the model to decide the settings for different parameters. The accuracy and robustness of the model will directly determine whether the ball can hit the target or how close the ball is landing to the target.

It is worthwhile to note the Catapult Project also gives students an opportunity to integrate business decision making to

engineering practice, as each team is allowed a maximum of 45 shots with no deduction of scores during the entire project. Upon completing the project, the students practice applying Six Sigma methodology to solve a real-life problem as well as obtaining the experience of improving the performance of the catapult while maintaining a profitable business.

THE 'JMP IN' SOFTWARE TRAINING

Other than traditional classroom lectures, the course also provides two or three training sections of the JMP In statistical software. The software is a statistical program that is widely used in Six Sigma methodology training and at companies such as Dow Chemical, Procter & Gamble, HP, and PPG. The software allows students to solve complicated statistical problems. For example, we have used the JMP In software to generate a contour plot to view all the possible combinations for desirable properties from the model developed in the factorial design.

CREATIVITY

Another learning impact of CHE 3343/4372, Engineering Experimentation, is on creativity. Most chemical engineering education focuses on problem solving based on well-established principles, placing less emphasis on creativity. Hueter states that modern people's "creative abilities increase in elementary school up to eight years old and then steadily decrease with further education, including college education."^[6,7] The importance of creativity in engineering can be summarized as follows: "Engineering is an art as well as a science, and good engineering depends upon leaps of imagination as well as painstaking care."^[7,8] Creativity is also heavily emphasized in Six Sigma methodology.^[9] The project, as well as a few

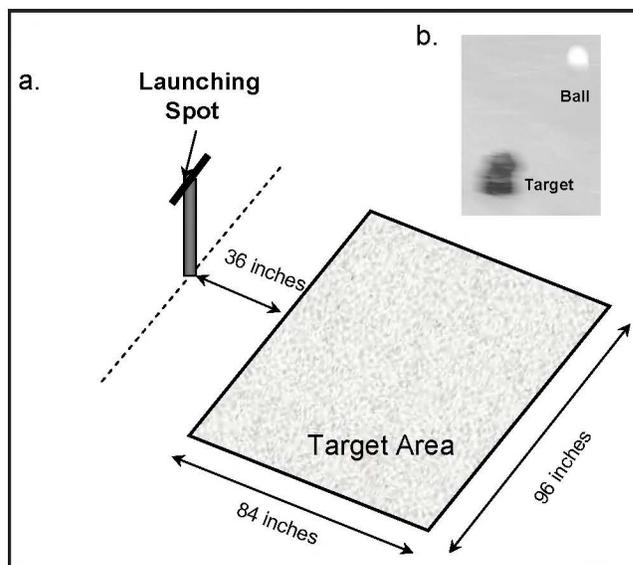


Figure 3. (a) A map illustrating the setup for the Catapult Project competition; (b) a ball is approaching the target in an actual competition in the class of 2004.

of the homework assignments (paper airplane competition, card drop exercises, etc.), provide students opportunities not only to practice the multidisciplinary methodology but also to maximize their potential to be creative during the exercises.

EVALUATION

The course is among the most popular electives in the chemical engineering curriculum at Texas Tech University. In the spring semesters of 2003-2006, the enrollment was 16, 26, 13, and 14, respectively. The course has received excellent student evaluation, with an average rating of 4.9/5.0, 5.0/5.0, 5.0/5.0, and 5.0/5.0 out of the 16 university-level questionnaires [scores rank from 1 (poor) to 5 (excellent)] on the instructor and course. Multiple students have said this class was their “favorite class” and the “best experience in a college course.” Specific comments related to the Six Sigma training and work experience include:

- “Taking this class has given me confidence in my ability to attack and solve problems at my new job this summer.”
- “I think this class was one of the most beneficial courses that I have taken.”
- “Really enjoyed this class being directly applicable to my work today.”
- “I’m glad that the department decided to give this course, with industry changing year to year. This class will be extremely useful when we go to work!”
- “Great course. It should be offered every year. It helped me get my job.”

SUMMARY

We have successfully incorporated Six Sigma methodology training into a traditional chemical engineering course, CHE 3343/4372, Engineering Experimentation, at Texas

Tech University. The course is structured along the Six Sigma D.M.A.I.C. process and different technical and nontechnical tools have been discussed in each stage of the process. Some of the nontraditional aspects in this course include industrial need, special homework assignments, the Catapult Project, the JMP In statistical software training, and emphasis on creativity. In addition, students have also obtained hands-on experience to practice Six Sigma methodology and a unique and integrative experience to practice engineering and business concepts simultaneously.

ACKNOWLEDGMENTS

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Process Dynamics and Control, 2nd Ed.

by Dale Seborg, Tom Edgar, and Duncan Mellichamp

Wiley (2003) \$138.95

Reviewed by

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First, I want to applaud the authors for making a substantial, well-thought-out revision to their textbook. I have used the book to teach my introductory process control course but had not really read the additional material in the new chapters until this review. I was very impressed with the depth and breadth of the material. I am amazed that the authors were able to eliminate so much material and yet not dilute the critical topics that are important to a first course. I know that it was a struggle to decide what to eliminate and what to keep, just due to the fact that three personalities were involved. They did an excellent job.

Since the authors did eliminate so much material, especially on digital control, I see the two versions being more like Volume 1 and Volume 1.5 (not quite two volumes) and working to complement each other in advanced courses in process control. I see potentially three semester courses (at least this is the way I would do it) from this text. The first one is a general process control course for all undergraduate chemical engineering students covering Chapters 1-9, 11-12, and 15-16; a course in advanced methods covering Chapters 13-14, 18-21 (bringing in material from the first edition); and an application toward plantwide control and plant design covering Chapters 10, 22-24, and all the Appendices.

For those working in the process control field the book is a good textbook as well as a good reference manual. Faculty that are not, however, yet are teaching process control might find the text intimidating and too complex. I asked a faculty member in my department who fits this category and is currently using the text and that was his feeling. I kept this in mind while reviewing the text and I could understand his feeling of insecurity with it. One way the text could be improved is to revisit the chapters I mentioned for an introductory course and work to rewrite it in such a way that faculty in this category could feel more comfortable with the material.

My comments on specific chapters are as follows. Chapter 1 needs more problems. I am disappointed that they took the block diagram out of this chapter. I have used it to tell students where we are going and why we need Chapters 2-7 and how each block represents certain chapters that we will

tie back together in Chapter 11 (what used to be Chapter 10). Chapter 2 is essentially the same as before just with some new problems (I particularly like the additional application on bioprocesses and the exercises). Chapter 3 is essentially the same but the authors should have left Exercises 3.16 and 3.20 in this edition. These were two of my most popular problems for homework. Chapter 4 also did not change much but could be made shorter by giving a general method using Section 4.3 material, which covers all cases. I like the addition of state-space formulation. Chapter 5 has been basically untouched, which I applaud, but it does have more good problems—something faculty always appreciate. Section 6.3.1 is a good addition to Chapter 6 and is explained well. I have always appreciated this chapter and I am glad to see it is even better. The problems are good, especially the ones reflecting new material and bio-systems engineering. For Chapter 7, I feel that all the emphasis on graphical methods should be removed and replaced with regression. In illustrating regression techniques I think it is more important to show how software packages would do this rather than to give the mathematical equations on how they are done. Although they give Matlab and Excel examples they do not show, step by step, how this is exactly done. I think professors and students would appreciate this detail.

Example 7.4 needs to be revised or removed. Who would fit Models 3 and 4 to that response? In addition, a better ARX or ARMAX model should give a better fit by the fact that Model 1 fit so well.

Chapter 8 is basically the same but this chapter has always needed, as it does now, more problems. Chapter 9 is done well but needs more explanation of hardware and more problems.

Other textbooks are much stronger in this material such as Riggs (2001). I just skipped the material in Chapter 10 and went straight to Chapter 11. It is good material but out of step with how I do my course. It is important for the material on plantwide control and design. I do not like the way the material in the new Chapter 11 has combined Chapters 10 and 11 from the first edition. I like to keep stability analysis separate. There are, however, plenty of good exercises in this chapter. Chapter 12 is done well and has excellent problems. Chapters 13 and 14 are a good condensation of the three chapters on frequency response from the first edition. This material needs to remain but not be overemphasized, in my opinion. Chapter 15 is an excellent chapter with good problems.

For Chapter 16, the addition of Fuzzy Logic Control is an excellent improvement but I couldn't find any exercises on this topic. In Chapter 17 I am glad that they left the material on filtering in this edition. I know that it was difficult to remove much of the material on z-transforms and sample data-control systems, but the first addition could supplement

these eliminations if necessary. It would help to actually have an example for obtaining the poles and zeros. Also, what happened to $C_0 U_z$ in Eq. 17-46? The C_0 is there but where is U_z ? I appreciate the addition of Section 17.6 and I am glad they did not go into a lot of detail [it would be hard to match the material of Ogunnaike and Ray (1994) on the topic]. There are a lot of good problems in the exercises.

I did not find many errors or typos in this edition, which is commendable considering the amount of new material and reorganization. In Chapter 18, however, “n!” on page 477 should be “n².” Also, on page 479, “hidden” is mistakenly printed as, “hidd en.” On page 492, just below Eq. 18-58, “4” should be “w.” I commend the authors for adding the SVD material and updating this chapter. It may be the most important chapter for the control design engineer in terms of theory.

I am glad that they shortened the material in Chapter 19 since optimization is a course in itself and only an overview is critical to any process control course. Chapter 20 is a substantial and critical improvement over the first edition. All the basic fundamentals and concepts of model predictive control (MPC) appear to be present. At least it gives a good overview

and introduction on the subject. Although I have not taught from this chapter yet, the exercises appear to be excellent.

The authors did an excellent job on Chapter 21. They did it just right and the critical material is here in just the right amount. These topics include the following: X bar chart, S chart, Cusum, EWMA, Cpk, Six Sigma, and multivariate MPC. They need, however, to point out which ones detect a “mean shift” vs. a “variance shift.” For example, there is no statement in this regard for the X bar chart. I suggest that they add the use of Minitab in this chapter as they did Matlab and Simulink for chapters exploiting their use. Finally, Chapters 22-24 appear to be done quite well and I look forward to using them in future courses.

Overall, the authors’ have made a timely and significant improvement to this textbook by bringing it up to date with current practices and needs, and enhancing its use as a textbook in process control for undergraduate as well as graduate students. I have used the earlier book since 1991, and with the improvements they have made in the second edition, this text will be useful in the courses I teach for many years to come. □

The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems that can be used to motivate the student by presenting a particular principle in class, 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 elucidate difficult concepts. Manuscripts should not exceed 14 double-spaced pages and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

INTRODUCING NON-NEWTONIAN FLUID MECHANICS COMPUTATIONS

With Mathematica in the Undergraduate Curriculum

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A non-Newtonian fluid has a viscosity that changes with the applied shear force. These fluids are characterized by measuring or computing several rheological properties, such as the viscosity and the first and second normal stresses. Rheometers are used, under oscillatory shear flow or extensional flow, to obtain experimental values of these rheological properties while kinetic theory calculations using dumbbells allow the prediction of these rheological properties. For a Newtonian fluid (such as water), the viscosity is independent of how fast you are stirring it. For a non-Newtonian fluid the viscosity is dependent. It gets easier or harder to stir faster for different types of non-Newtonian fluids. By adding corn starch to water, one obtains a non-Newtonian fluid. Applying agitation with a spoon makes the fluid behave like a solid. Thus, the shear-thickening property of this non-Newtonian fluid becomes apparent. When agitation is stopped and the fluid is allowed to rest for a certain period of time, it recovers its liquid-like behavior.

Non-Newtonian fluids display many peculiar phenomena that can serve as the basis for multiple “fun” experiments students can perform in the laboratory. These include dye

swelling, rod climbing, and suspensions of particles behavior while moving in non-Newtonian vs. Newtonian fluids. Students can determine the terminal fall velocity and rotation direction of a single settling particle as well as wall effects and interaction between particles. Problems involving non-Newtonian fluid flow are ubiquitous in modern industry, such as in polymer processing plants. The study of body fluids such as blood, which is non-Newtonian, has important applications in biomedical engineering. In the present paper, we show how one can use the mathematical software Mathematica to



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solve some simple non-Newtonian fluid problems. The most relevant Mathematica commands^[1] are inserted in the text and can be found in any introductory book such as *Mathematica, A System for Doing Mathematics by Computer* by Stephen Wolfram.^[2] We start by reminding the reader of the few simple constitutive equations for the power-law, Carreau, and Bingham fluids. Then, we give the velocity profile for the horizontal flow of power-law and Carreau fluids in a pipe and an annulus. The velocity profile for the fall of a Bingham liquid film is obtained in the next section. We also derive volumetric flow rate expressions for pipe flow of Bingham and power-law fluids. In the last part of the paper, we make a model determination using previously found volumetric flow rate expressions and representative data.

CONSTITUTIVE EQUATIONS FOR NON-NEWTONIAN FLUIDS

For Newtonian fluids, the shear stress, τ , is proportional to the strain rate, $\dot{\gamma}$

$$\tau = \eta \dot{\gamma} \quad (1)$$

where the viscosity, η , the proportionality factor, is constant. The situation is different for non-Newtonian fluids, and the viscosity is a function of the strain rate:

$$\tau = \eta(\dot{\gamma}) \dot{\gamma} \quad (2)$$

Different constitutive equations, giving rise to various models of non-Newtonian fluids, have been proposed in order to express the viscosity as a function of the strain rate. In power-law fluids, the following relation is satisfied:

$$\eta = \kappa \dot{\gamma}^{n-1} \quad (3)$$

Dilatant fluids correspond to the case where the exponent in Eq. (3) is positive ($n > 1$) while pseudo-plastic fluids are obtained when $n < 1$. We see that viscosity decreases with strain rate for $n < 1$, which is the case for pseudo-plastic fluids, also called shear-thinning fluids. On the other hand, dilatant fluids are shear-thickening. If $n = 1$, one recovers the Newtonian fluid behavior.

The Carreau model describes fluids for which the viscosity presents a plateau at low and high shear rates separated by a shear-thinning region:

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = \frac{1}{[1 + (\lambda \dot{\gamma})^2]^{(1-n)/2}} \quad (4)$$

where η_0 is the zero-shear viscosity and η_∞ is the infinite-shear viscosity.

Finally, the Bingham model is defined as follows:

$$\text{At low shear rates : } \frac{1}{2}(\tau : \tau) \leq \tau_0^2, \quad \dot{\gamma} = 0 \quad (5)$$

$$\text{At high shear rates : } \frac{1}{2}(\tau : \tau) > \tau_0^2, \quad \tau = \left(\eta + \frac{\tau_0}{\dot{\gamma}} \right) \dot{\gamma} \quad (6)$$

HORIZONTAL FLOW OF CARREAU AND POWER-LAW FLUIDS IN A PIPE

Problem Statement

Find the velocity profiles for the laminar flow of power-law and Carreau fluids in a pipe, shown in Figure 1. Use the following values for the pressure difference ΔP , the exponent n , the Newtonian fluid viscosity η , the consistency index κ , the infinite-shear viscosity η_∞ , the zero-shear viscosity η_0 , the relaxation parameter λ , the pipe length L , and radius R , whose units appear under "Nomenclature" at the end of this article:

$$\Delta P = 100; \quad L = 50; \quad \text{and} \quad R = 0.02$$

$$\text{Newtonian fluid: } \eta = 8.9 \times 10^{-4}.$$

$$\text{Dilatant fluid: } n = 3.39 \text{ and } \kappa = 10^{-6}.$$

$$\text{Pseudo-plastic fluid: } n = 0.4 \text{ and } \kappa = 5 \times 10^{-3}.$$

$$\text{Carreau fluid: } n = 0.5, \lambda = 0.2, \eta_0 = 1.72 \times 10^{-3}, \text{ and } \eta_\infty = 0.$$

Solution

This problem is treated using Polymath, a numerical computational package,^[3] in *Problem Solving in Chemical Engineering with Numerical Methods* by Cutlip and Shacham.^[4] The governing equation is the z-component of the equation of motion in cylindrical coordinates:

$$\frac{1}{r} \frac{d}{dr} \left[r \kappa \left(-\frac{dv_z}{dr} \right)^n \right] = \frac{\Delta P}{L} \quad (7)$$

Eq. (7) is subject to the following split boundary conditions:

$$\text{At } r = 0 : \quad \tau_{rz} = 0 \quad (8)$$

$$\text{At } r = R : \quad v_z = 0 \quad (9)$$

These kinds of mathematical problems often require the use of a particular numerical approach called the shooting technique. This method consists of guessing different values of v_z at $r = 0$, solving the differential equation, and checking that the no-slip boundary condition at $r = R$ is satisfied. An analytical solution is possible for power-law fluids and details about its derivation can be found in *Fluid Mechanics for Chemical Engineers* by Wilkes:^[5]

$$v_z(r) = \left(\frac{\Delta P}{L} \frac{1}{2\kappa} \right)^{1/n} \frac{(R^{1+1/n} - r^{1+1/n})}{\frac{1}{n} + 1} \quad (10)$$

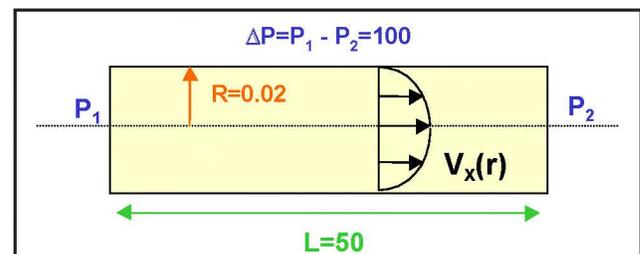


Figure 1. Flow of Carreau and power-law fluids in a pipe.

For the Carreau fluid, one must use a numerical approach since no analytical solution is available.

For the power-law fluids, the following Mathematica commands are used to find the velocity:

```

system[Ω_] = { D[r τrz[r], {r, 1}] == ΔP/Lr,
  D[vz[r], {r, 1}] == If[τrz[r] ≥ 0, -(τrz[r]/κ)^(1/n),
    (-τrz[r]/κ)^(1/n)], τrz[10^-5] == 0, vz[10^-5] == Ω };
myODEsoln[Ω_] := NDSolve[system[Ω], {vz, τrz}, {r,
  10^-5, R}]
yend[Ω_?NumericQ] := Flatten[{vz[r] /. myODEsoln[Ω]}
  /. r -> R]
bc = FindRoot[yend[Ω] == 0, {Ω, 0, 0.5}][[1, 2]];

```

The graphical capability of Mathematica allows the student to plot the velocity profile without having to use different software. Figure 2 shows the velocity profile for the Newtonian, dilatant, Carreau, and pseudo-plastic cases using the commands:

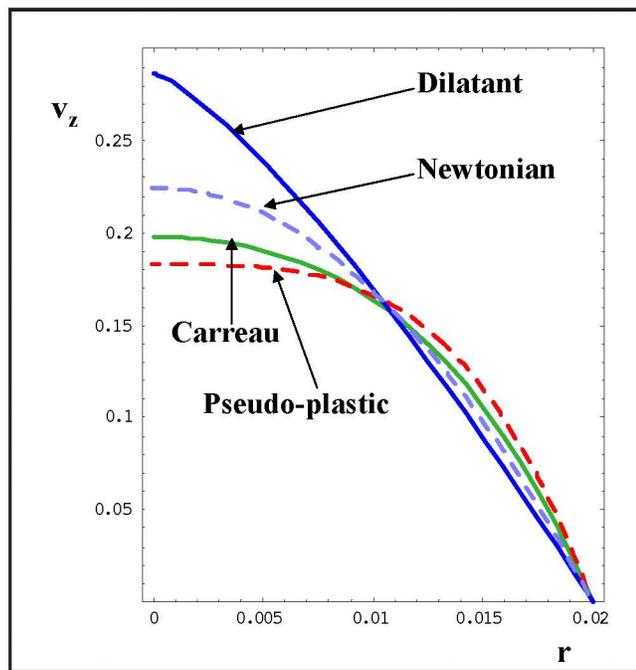


Figure 2. Velocity profiles of dilatant, pseudo-plastic, Carreau, and Newtonian fluids in a pipe.

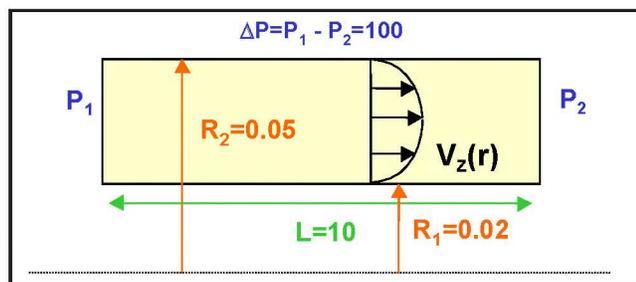


Figure 3. Flow of Carreau and power-law fluids in an annulus.

```

sol1=myODEsoln[bc]
plt1=Plot[vz[r] /. sol1, {r, 0.00001, R}, PlotStyle -> RGB-
  Color[0, 0, 1]]

```

These profiles are obtained under equal volumetric flow conditions. The velocity near the wall is higher for Carreau and pseudo-plastic fluids than for Newtonian and dilatant fluids. This results in higher heat transfer rates due to a higher convection. The approach to solve split boundary problems using Mathematica is more systematic than the one proposed by Cutlip and Shacham^[4] using Polymath, despite a steeper initial learning curve for students. In fact, it automatically finds the velocity at the center of the pipe by verifying the no-slip boundary condition and using the Mathematica command *FindRoot*.

HORIZONTAL FLOW OF A CARREAU AND A POWER-LAW FLUID IN AN ANNULUS

Problem Statement

Find the velocity profiles for the laminar flow of power-law and Carreau fluids in an annulus, shown in Figure 3. Use the following values, where R_1 and R_2 are the inner and outer radii, and all other symbols have already been defined:

$$\Delta P = 100; \quad L = 50; \quad R_1 = 0.02 \quad \text{and} \quad R_2 = 0.05$$

$$\text{Newtonian fluid: } \eta = 8.9 \times 10^{-4}.$$

$$\text{Dilatant fluid: } n = 1.2 \quad \text{and} \quad \kappa = 4.7 \times 10^{-4}.$$

$$\text{Pseudo-plastic fluid: } n = 0.5 \quad \text{and} \quad \kappa = 4.5 \times 10^{-3}.$$

$$\text{Carreau fluid: } n = 0.5, \lambda = 0.2, \eta_0 = 2.04 \times 10^{-3} \quad \text{and} \quad \eta_\infty = 0.$$

Solution

Cutlip and Shacham^[4] have solved this example using Polymath. The governing equation is again the z-component of the equation of motion in cylindrical coordinates:

$$\frac{1}{r} \frac{d}{dr} \left[r \tau_{rz} \left(-\frac{dv_z}{dr} \right)^n \right] = \frac{\Delta P}{L} \quad (11)$$

Eq. (11) is subject to the following split boundary conditions:

$$\text{At } r = R_1 : \quad v_z = 0 \quad (12)$$

$$\text{At } r = R_2 : \quad v_z = 0 \quad (13)$$

To solve this problem, we make use of the shooting technique in a similar fashion as the previous example. This method works by guessing different values of τ_{rz} at $r = R_1$, solving the differential equation, and checking that the no-slip boundary condition at $r = R_2$ is satisfied. An analytical solution^[4] is available for the Newtonian fluid case:

$$v_z(r) = \left(\frac{\Delta P}{4\eta L} \right) \left[R_2^2 - r^2 + \frac{R_2^2 - R_1^2}{\ln(R_2 / R_1)} \ln(r / R_2) \right] \quad (14)$$

There is no analytical solution for dilatant, pseudo-plastic, and Carreau fluids, so one must resort to a numerical method.

For the power-law fluids, the following Mathematica command is used to find the velocity as a function of r :

```
system[Ω_] := { D[r τrz[r],{r,1}] == ΔP/L r,
  D[vz[r],{r,1}] == If[τrz[r] ≥ 0, -(τrz[r]/κ)^(1/n),
  (-τrz[r]/κ)^(1/n)], τrz[R1] == Ω, vz[R1] == 0 };
myODEsoln[Ω_] := NDSolve[system[Ω], {vz, τrz}, {r, R1, R2}]
yend[Ω_?NumericQ] := Flatten[{vz[r] /. myODEsoln[Ω]}
/. r → R2]
bc = FindRoot[yend[Ω] == 0, {Ω, -2, 2}][[1,2]];
```

One can plot the velocity profile, shown in Figure 4, for the Newtonian, dilatant, Carreau, and pseudo-plastic cases using the Mathematica commands:

```
sol1=myODEsoln[bc]
plt1=Plot[vz[r] /. sol1, {r, 0.00001, R}, PlotStyle → RGB-Color[0, 0, 1]]
```

These profiles are obtained under equal volumetric flow conditions. The velocity profiles found for all four fluids are not symmetric. In fact, they reach a maximum value close to the radial position, given by $r = 0.033$, slightly less than halfway from R_1 and R_2 .

VERTICAL LAMINAR FLOW OF A BINGHAM LIQUID FILM

Problem Statement

Find the velocity profile for the vertical laminar flow of a Bingham fluid down the wall depicted in Figure 5. Values of the gravitational acceleration, g , the density, ρ , the yield stress, τ_0 , the zero-shear viscosity, η_0 , the film thickness, δ , are given by:

$$g = 9.81; \quad \rho = 950; \quad \tau_0 = 5; \quad \eta_0 = 0.15 \text{ and } \delta = 0.005$$

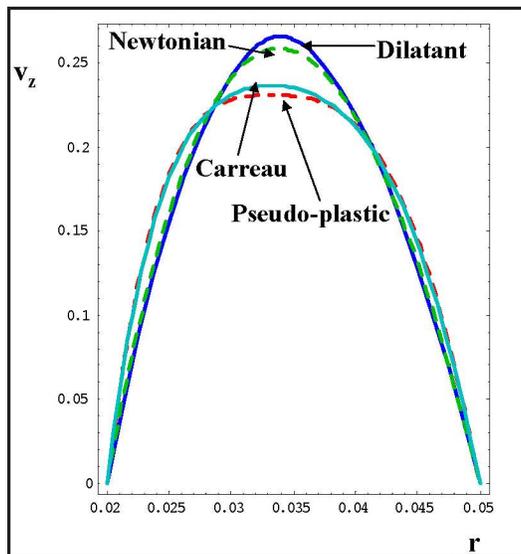


Figure 4. Velocity profiles of dilatant, pseudo-plastic, Carreau, and Newtonian fluids in an annulus.

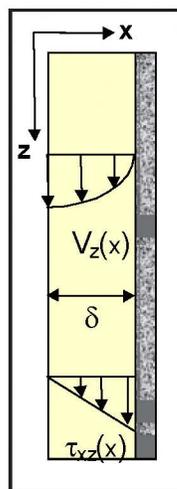


Figure 5. Vertical flow of a Bingham fluid in a liquid film.

Solution

Cutlip and Shacham^[4] have presented a solution of this example using Polymath. The governing equation is the z -component of the equation of motion in rectangular coordinates:

$$\frac{d\tau_{xz}}{dx} = \rho g \quad (15)$$

Eq. (15) is subject to the following split boundary conditions:

$$\text{At } x = 0: \quad \tau_{xz} = 0 \quad (16)$$

$$\text{At } x = \delta: \quad v_z = 0 \quad (17)$$

We make the same treatment as the first two problems by applying the shooting technique:

```
system[Ω_] := { D[τxz[x],{x,1}] == ρ g,
  D[vz[x],{x,1}] == If[Abs[τxz[x]] ≤ τ0, 0,
  If[τxz[x] > τ0, (τ0 - τxz[x]) / η0, -(τ0 + τxz[x]) / η0 ]],
  τxz[0] == 0, vz[0] == Ω };
myODEsoln[Ω_] := NDSolve[system[Ω], {vz, τxz}, {x, 0, δ}]
yend[Ω_?NumericQ] := Flatten[{vz[r] /. myODEsoln[Ω]}
/. r → δ]
bc = FindRoot[yend[Ω] == 0, {Ω, 0, 0.5}][[1,2]];
```

For the Newtonian case, an analytical expression for the velocity, v_z , as a function of position, x , can be easily derived:

$$v_z = \frac{\rho g \delta^2}{2\eta} \left[1 - \left(\frac{x}{\delta} \right)^2 \right] \quad (18)$$

In Figure 6, we show the velocity profile for the Newtonian and the Bingham fluids. This plot is obtained by using the Mathematica commands:

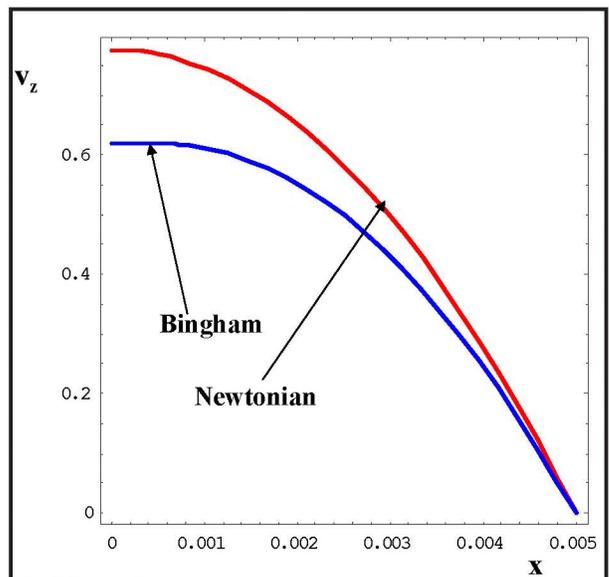


Figure 6. Velocity profiles of Bingham and Newtonian fluids in a liquid film.

```
sol1=myODEsoln[bc]
plt1=Plot[vz[x]/. sol1, {x, 0, δ}, PlotStyle → RGBColor[0, 0, 1]]
```

A comparison of the velocity profile obtained using the analytical solution for the Newtonian fluid and the velocity profile corresponding to the Bingham fluid shows that the latter is flat near the surface of the liquid film. In fact, we have a nonzero velocity gradient only when $\tau_{xz} > \tau_0$. This behavior is typical of Bingham fluids.

EXPRESSIONS OF VOLUMETRIC FLOW RATES

Problem Statement

Derive expressions of volumetric flow rates for pipe flow of Bingham and power-law fluids using symbolic computations with Mathematica.

Solution

Power-law fluid case

First, we find the expression of the shear stress, τ_{rz} , as a function of the radial position, r :

```
sol3 = DSolve[D[r τrz[r], {r, 1}] == - ΔP/L r, τrz[r], r]
τrz[r] = sol3[[1, 1, 2]]/. C[1] → 0
```

We get the following result:

$$\tau_{rz} = -\frac{\Delta Pr}{2L} \quad (19)$$

Then, we determine the velocity distribution using the symbolic command, *Dsolve*,

```
sol4 = DSolve[D[vz[r], {r, 1}] == -(-τrz[r]/κ)^(1/n), vz[r], r]
vz[r] = sol4[[1, 1, 2]] /. C[1] →  $\frac{2^{-1/n} nR \left(\frac{\Delta PR}{\kappa L}\right)^{1/n}}{1+n}$ 
```

Finally, the symbolic command, *Integrate*, is used,

```
Q = Integrate[2 Pi r vz[r], {r, 0, R}]
```

TABLE 1 Volumetric Flow Rate vs. Pressure Gradient	
ΔP/L (Pa/m)	10 ⁵ × Q (m ³ /s)
10000	5.37
20000	26.4
30000	68.9
40000	129
50000	235
60000	336
70000	487
80000	713
90000	912
100000	1100

and we get the following expression for the volumetric flow rate,

$$Q = \frac{2^{-1/n} \pi R^3 n \left(\frac{R \Delta P}{\kappa L}\right)^{1/n}}{1+3n} \quad (20)$$

Bingham fluid case

Just like the treatment above, we start by finding the expression of the shear stress, τ_{rz} , as a function of the radial position, r :

```
sol1 = DSolve[D[r τrz[r], {r, 1}] == - ΔP/L r, τrz[r], r]
τrz[r] = sol1[[1, 1, 2]]/. C[1] → 0
```

We get the following result:

$$\tau_{rz} = -\frac{\Delta Pr}{2L} \quad (19)$$

In the first part of the derivation, we determine the velocity distribution between $r = (2\tau_0 L)/\Delta P$ and $r = R$ using boundary condition $v_z(R) = 0$ and the symbolic command, *Dsolve*:

```
sol2 = DSolve[D[vz[r], {r, 1}] == (τrz[r]+τ0)/η, vz[r], r]
vz[r] = sol2[[1, 1, 2]] /. C[1] → ((ΔP R^2)/(4 η L)) - (Rτ0)/η
```

The symbolic command, *Integrate*, is used to obtain the expression of the volumetric flow rate between $r = (2\tau_0 L)/\Delta P$ and $r = R$,

```
Q1 = Integrate[2 Pi r vz[r], {r, 2 τ0 L/ΔP, R}]
```

In the second part of the derivation, we determine the constant velocity, v_0 , between $r = 0$ and $r = (2\tau_0 L)/\Delta P$ using the following symbolic command:

```
v0 = 1/μ (-ΔP/L) (r^2-R^2)/4 + τ0/μ (r-R) /. r → 2τ0 L/ΔP
```

This is nothing more than expressing the continuity of the velocity at $r = (2\tau_0 L)/\Delta P$. In fact, we have written that $v_0 = v_z((2\tau_0 L)/\Delta P)$ in the above Mathematica statement.

The symbolic command, *Integrate*, is used to obtain the expression of the volumetric flow rate between $r = 0$ and $r = (2\tau_0 L)/\Delta P$,

```
Q2 = Integrate[2 Pi r v0, {r, 0, 2τ0 L/ΔP}]
```

and we get the following expression for the overall volumetric flow rate,

$$Q = \frac{\pi R^4 \Delta P}{8 \eta L} - \frac{\pi R^3 \tau_0}{3 \eta} + \frac{2 \pi \tau_0^4 L^3}{3 \eta \Delta P^3} \quad (21)$$

NON-NEWTONIAN FLUID MODEL DETERMINATION

Problem Statement

Wilkes^[5] provides representative values of the volumetric flow rate vs. the applied pressure gradient for horizontal flow in a pipe. These values are reproduced in Table 1. The pipe radius is equal to $R = 0.01\text{m}$. Use these representative values,

in conjunction with the analytical expression of the volumetric flow rates determined in the previous section, to compute the parameters of the constitutive equation.

Solution

First, we compute the following sum:

$$J = \sum_{i=1}^{10} (Q_i^{\text{rep}} - Q_i^{\text{th}})^2 \quad (22)$$

where Q_i^{rep} and Q_i^{th} are the representative value and analytical expression of the volumetric flow rate. Then, we use the built-in command of Mathematica, *FindMinimum*, to determine the values of n and κ for the power-law model, and τ_0 and η for the Bingham model that minimize the objective function, J . The approach used here is the least squares method. For the power-law model, we find $n = 0.437$ and $\kappa = 6.708$, while for the Bingham model the result is $\tau_0 = 77.55$ and $\eta = 0.0326$. The value of the sum given by Eq. (22) is 9.89×10^{-6} for the Bingham model and 2.67×10^{-7} for the power-law model. Thus, we conclude that the power-law model fits the representative data better.

CONCLUSIONS

We presented the solution of four non-Newtonian fluid mechanics problems using Mathematica. The velocity profile is obtained for the horizontal flow of power-law and Carreau fluids in pipes and annuli, and for the vertical laminar flow of a Bingham fluid. These problems have split boundary conditions and were solved using the shooting techniques. Analytical expressions of volumetric flow rates for pipe flow of the Bingham and power-law fluids were derived using Mathematica. The parameters of the constitutive equation of non-Newtonian fluids were obtained from representative data of flow rates measured under different applied pressure gradients in a horizontal pipe. These problems are simple enough to constitute an excellent introduction to the field of non-Newtonian fluid mechanics. Students at the National Institute of Applied Sciences in Tunis performed well despite no previous knowledge of Mathematica. Mathematica

notebooks are available from author upon request or at the information center.^[1]

NOMENCLATURE

g	gravitational acceleration (m/s ²)
Q	volumetric flow rate (m ³ /s)
L	pipe length (m)
n	power-law exponent
ΔP	pressure difference (Pa)
R	pipe radius (m)
R_1, R_2	annulus radii (m)
r	radial position (m)
v_z	velocity (m/s)
z	axial position (m)
κ	power-law consistency index (N · s ⁿ /m ²)
δ	film thickness (m)
λ	relaxation parameter (s)
η	viscosity (kg/m · s ²)
η_0	zero-shear viscosity (kg/m · s ²)
η_∞	infinite-shear viscosity (kg/m · s ²)
ρ	density (kg/m ³)
τ_0	yield stress (kg/m · s)
τ_{rz}	shear stress (kg/m · s)

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IMPLEMENTATION AND ANALYSIS OF HEMODIALYSIS

in the Unit Operations Laboratory

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The recent boom in the biomedical/biochemical industry has necessitated the introduction of biological components into the chemical engineering curriculum. According to the U.S. Department of Labor, the job market for biomedical engineers is projected to increase 31.4% through 2012.^[1] In 1990, less than 4,000 students were enrolled in undergraduate biomedical/biochemical programs; in 2002 there were more than 10,000 students enrolled.^[2] In the next five years, it is estimated that two to three times more students per year will take biomedical/biochemical courses.

To enhance biomedical/biochemical engineering opportunities in chemical engineering, experiments involving enzymatic degradation of cellulose and dialysis of creatinine were introduced at Oklahoma State University (OSU) in the Unit Operations Laboratory (UOL). These projects enhance the instruction students receive in optional Introduction to Biomedical Engineering and Introduction to Bioprocess Engineering courses. In the UOL, students work in teams of

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three participating in three five-week projects during each semester. While assigning projects, bio-related ones are allocated preferentially to students enrolled or committed to biomedical and/or bioprocess courses.

The dialysis experiment demonstrates the fundamental concepts of a hemodialysis device using creatinine as the target agent for removal. Creatinine (MW 113) is one of several waste products produced in a human that must be removed by the kidney. Although some dialysis experiments have previously been demonstrated in the chemical engineering curriculum using salt solutions with short experimental times,^[3] the use of creatinine has several advantages. These advantages include its larger relative size to other waste products and its use, along with urea, as a marker for effective dialysis treatment.^[4] The larger creatinine size leads to a longer removal time in comparison to other waste products. The waste product with the longest removal time is often used in determining dialysis treatment time. Thus, the use of creatinine leads to a more realistic dialysis experiment—even with the drawback of longer dialysis time. This work presents a dialysis model that demonstrates the assessment of model assumptions. It will detail the dialysis project statement delivered to the student team, the experimental protocol, the dialysis model, experimental results, and student feedback and assessment. A benefit of incorporating the dialysis project is that the student can integrate a number of concepts such as material balances/modeling (*i.e.*, blood and dialysate balances with assumptions), transport issues (*i.e.*, evaluation of transport coefficients), model validation of assumptions, and solving differential equations (*i.e.*, using Polymath) toward a bioengineering project that allows the student to expand the scope of his/her chemical engineering education.

PROJECT STATEMENT

A biomedical engineering company makes many biomedical devices, one of which is a hollow-fiber separator for dialysis machines. Hospitals use dialysis to process the blood of patients whose kidneys do not effectively remove toxins and excess water from the blood. The machine has many features that you will not need to use. We are interested in the hollow-fiber membrane separation unit that dialyzes the blood. Please develop and validate an unsteady-state model for predicting the temporal profile depicting creatinine removal, one of several toxic metabolites, from “blood” (represented by water in this experiment). Using your model, determine the effects on dialysis treatment time, blood recirculation flow rate, and transmembrane pressure (ΔP) for removing 90% of creatinine. Metabolites and electrolytes affect the osmotic pressure, which affects the transport of water across the membrane. This osmotic pressure effect must be included in your model to determine the amount of water removed from (or added to) the “blood” during the dialysis treatment.

As part of the model, you need to generate experimental data from the hollow-fiber membrane separator to obtain an overall transfer coefficient for creatinine and then you must validate your model. The hollow-fiber membrane unit is similar to a shell-and-tube heat exchanger. Basically, blood flows through the inside of the hollow fibers (tubes), and dialysate (composed of salts similar to normal blood concentrations) flows through the shell-side. Unwanted toxins and other excess metabolites and electrolytes in the blood diffuse through the fiber walls into the dialysate. The patient’s blood is continuously circulating within his/her body. The blood compartment of the body can be assumed as a Continuous Stirred Tank (CST) in which the partially purified blood coming from the kidney dialysis unit is returned to the body.

EXPERIMENTAL PROTOCOL

The experiment consists of a hemodialysis unit connected to a bucket of water containing creatinine (representing the patient’s blood), as shown in Figure 1. A schematic of the

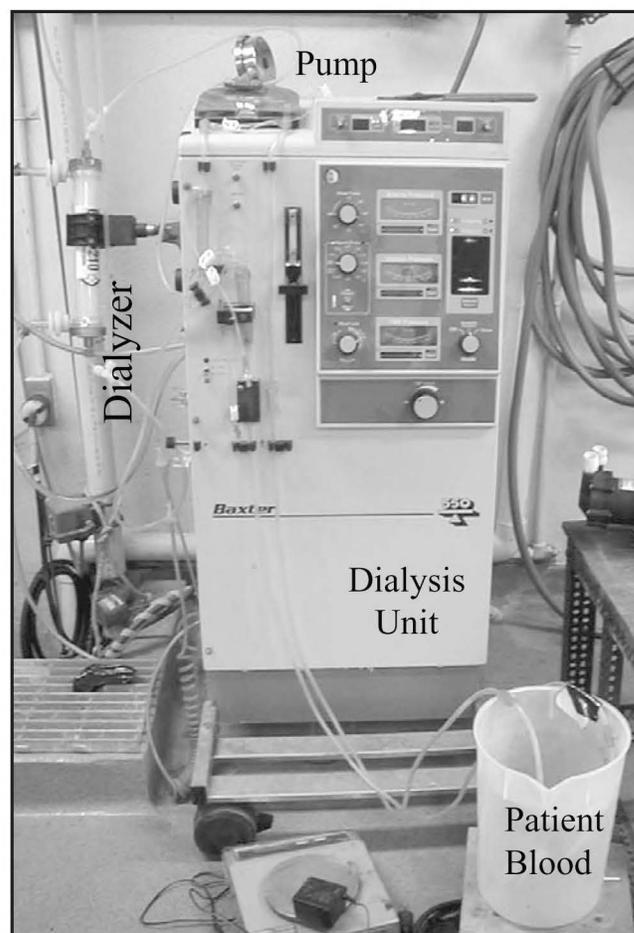


Figure 1. Dialysis unit, dialyzer, and a continuously stirred tank containing creatinine that represents the patient’s blood.

experimental system is shown in Figure 2. Although hemodialysis units are expensive, many dialysis centers regularly replace their units on an annual or bi-annual basis. Since there is often a cost for disposal of the units, the supplier of hemodialysis units at a local dialysis center was contacted and the supplier donated 10 units to OSU at no charge. It is likely that such donations can be obtained from other hemodialysis unit suppliers in the same fashion. Manometers were placed at all inlets and outlets of the dialyzer to measure pressure drops from one end of the dialyzer to the other end as well as to measure transmembrane pressure differences. Three to four liters of a solution (denoted “blood”) containing up to 4.1 mM creatinine were used to simulate the patient’s initial blood concentration. The blood was continuously mixed using a magnetic stirrer. The blood was pumped to the tube side of the dialyzer at rates varying between 300-500 ml/min, controlled by the dialysis unit, and blood volume changes were monitored at regular intervals by weighing the bucket on an electronic scale. Water (denoted “dialysate”) was continuously added at rates between 815-865 ml/min to the shell side of the dialyzer and, upon exiting, emptied into a waste sink.

Experiments were conducted over a two-hour period. In the open-loop experiment, the blood flowed such that the blood entering the dialyzer from the bucket contained a constant creatinine concentration and the blood exiting the dialyzer was sent to a waste bucket. This experiment was performed to determine the creatinine mass transfer parameter, K_c , necessary to predict the creatinine concentration with time in the closed-loop experiment. In the closed-loop experiment, the blood continuously circulated such that the blood volume and creatinine concentration decreased with time. The changing creatinine concentration was used to compare model predictions with experimental results. During the experiments, the inlet and outlet pressures across the dialyzer and the volume of the blood were recorded every five minutes (via measuring the weight of the blood). Samples (0.3-0.5 mL) were collected for analysis of the creatinine concentration.

To analyze the creatinine concentration, one part sample was mixed with three parts of a solution containing a 10:1 ratio of 0.14% picric acid and sodium hydroxide. Note that picric acid is hazardous, highly explosive, and should only be used under the careful guidance of an instructor. In this analysis, creatinine reacts with alkaline picrate to form a reddish-yellow solution from which the absorbance can be detected in a spectrophotometer at 490 nm.^[5] The absorbances were converted to concentrations via a linear calibration curve. Spectrophotometers are a common component in many laboratories and thus there is a possibility that arrangements could be made to use existing spectrophotometers for the creatinine analysis. Inexpensive spectrophotometers may be purchased, however, for as little as \$1,500. Other calorimetric methods also exist for assaying creatinine, although the methods are more expensive.^[6]

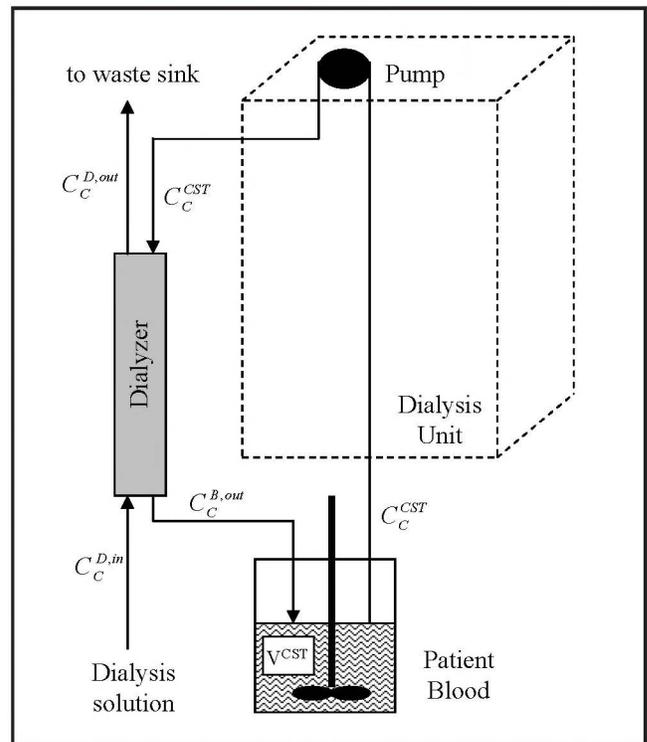


Figure 2. Schematic of Figure 1 showing the dialysis unit and countercurrent flow in the dialyzer. The creatinine concentration (C) parameters and volume (V^{CST}) of the continuously stirred tank used in Eqs. (2) and (3) and (7) through (9) are shown.

DIALYSIS MODEL AND SOLUTION

To meet the objectives of the project statement, students needed to develop a mathematical model for the process. The blood in the bucket was modeled as a CST with a given volume (V^{CST}). During the closed-loop experiment, the CST creatinine concentration (C_c^{CST}) changes with time according to:

$$\frac{dC_c^{CST}}{dt} = \frac{Q^{B,out}}{V^{CST}} (C_c^{B,out} - C_c^{CST}) \quad (1)$$

where $Q^{B,out}$ is the volumetric outlet flow rate of blood through the dialyzer and $C_c^{B,out}$ is the “blood” creatinine concentration exiting the dialyzer (and entering the CST). Since the CST volume changes with time, the creatinine material balance and the total mass balance (assuming constant density) were combined to obtain Eq. (1). The total mass balance, assuming constant density, is represented by:

$$\frac{dV^{CST}}{dt} = Q^{B,out} - Q^{B,in} \quad (2)$$

where $Q^{B,in}$ is the volumetric inlet flow rate of blood through the dialyzer. To solve Eqs. (1) and (2) to predict V^{CST} and C_c^{CST} with time (as part of the project statement objective), it is important to know how $C_c^{B,out}$ and $Q^{B,out}$ are related to

dialyzer inlet conditions. $Q^{B,in}$ is constant and set by the dialysis machine.

Material balances around the dialyzer identify the inter-relationship between $C_c^{B,out}$ and $Q^{B,out}$, and demonstrate how these parameters can be used in Eqs. (1) and (2) to predict V^{CST} and C_c^{CST} with time. Assuming countercurrent flow between the blood and dialysate, the material balances around the dialyzer are:

$$Q^{B,in} - Q^{B,out} = Q^{D,out} - Q^{D,in} = \alpha \Delta P A_M \quad (3)$$

$$\frac{dC_c^B}{dA} = \frac{K_C}{Q^B} (C_c^D - C_c^B) \quad (4)$$

$$\frac{dC_c^D}{dA} = \frac{\alpha \Delta P + K_C}{Q^D} (C_c^D - C_c^B) \quad (5)$$

Eq. (3) represents that total water loss from the blood side into the dialysate side following a single pass, resulting from the average transmembrane pressure difference (ΔP) between the blood and dialysate. Q^B and Q^D are the blood-side and dialysate-side volumetric flow rates. ΔP is often constant and can be approximated as $\Delta P = P_B^{avg} - P_D^{avg}$ where P_B and P_D are the average pressures of blood and dialysate, respectively. The convective transport coefficient for water across the dialyzer membrane is represented by α , and A_M is the total transport area of the membrane. For the dialyzer used in this study, $A_M = 1.5 \text{ m}^2$ (CL T150L, Terumo Medical Corporation, Tokyo, Japan). Eq. (4) is the material balance for creatinine in the blood side (C_c^B) of the dialyzer where K_C is the mass transfer coefficient of creatinine (units of length per time) describing diffusive transport of creatinine across the membrane relative to convective flow. Eq. (5) is the material balance for creatinine in the dialysate side (C_c^D) of the dialyzer. The differential membrane transport area with integration proceeding from the blood inlet to the blood outlet is represented by dA .

The assumptions in the development of Eqs. (3) to (5) include: 1) pseudo-steady state material balances, 2) plug flow, 3) constant ΔP , and 4) the Staverman reflection coefficients (σ) for all solutes have a value of zero. Note that σ has a value ranging from 0, denoting solute flows unimpeded through the membrane, to 1, in which solute is completely reflected by the membrane and only diffusion occurs.^[4] When $\sigma=0$ for all solutes, there is no osmotic driving force for water transport. For this study, the small MW of creatinine (113 Da) relative to the average pore size of the dialyzer (8,000-10,000 Da) leads to $\sigma \approx 0$ for creatinine.^[4] For analysis involving co-current dialysate flow, the term $Q^{D,out} - Q^{D,in}$ in Eq. (3) is replaced with $Q^{D,in} - Q^{D,out}$, and the differential sign in Eq. (5) is negative.

The parameters α and K_C must be assessed to use the model. To obtain α , the closed-loop experiment is performed in the absence of solutes (or the presence of any solute as long as $\sigma=0$ for the solute) by measuring ΔP and the changing V^{CST} . Combining Eq. (3) with Eq. (2) suggests that a plot of V^{CST} vs. time yields a slope of $-\alpha \Delta P A_M$. Thus, the measurement of ΔP with the known value of A_M enables the calculation of α .

K_C can easily be obtained when $\alpha \Delta P \ll K_C$ for Eq. (5) and $\alpha \Delta P A_M$ is very small compared to $Q^{B,in}$ and $Q^{D,in}$ for Eq. (3), such that $Q^{B,out} \approx Q^{B,in}$ and $Q^{D,out} \approx Q^{D,in}$ (i.e., Q^D and Q^B are constant) according to Eq. (3). For these assumptions, integration of Eqs. (4) and (5) results in $C_c^{B,out} = C_c^{CST} (1-E)$ where E is

$$E = \frac{1 - \exp[-N_T(1+z)]}{(1+z)} \quad \text{co-current flow} \quad (6)$$

$$E = \frac{\exp[N_T(1-z)] - 1}{\exp[N_T(1-z)] - z} \quad \text{countercurrent flow} \quad (7)$$

and N_T and z are $K_C A_M / Q^{B,in}$ and $Q^{B,in} / Q^{D,in}$, respectively.^[7] The parameter K_C can be obtained from the open-ended experiment with a known z by measuring C_c^{CST} (also equivalent to $C_c^{B,in}$) and $C_c^{B,out}$, solving for E , solving for N_T from either Eq. (6) or (7), and then solving for K_C at the given $Q^{B,in}$ and A_M . The validity of the assumptions can be assessed by comparing $\alpha \Delta P$ with K_C and $\alpha \Delta P A_M$ with $Q^{B,in}$ and $Q^{D,in}$. The validity of assumptions should always be checked when applying models. Thus, the dialysis project is an excellent tool for allowing students to demonstrate the validation of assumptions.

Once values of α and K_C are known, V^{CST} and C_c^{CST} can be predicted with time for fixed dialysate and blood inlet flow rates (i.e., a given z value) by utilizing $C_c^{B,out} = C_c^{CST} (1-E)$ and $Q^{B,out} = Q^{B,in} - \alpha \Delta P A_M$ in the integration of Eqs. (1) and (2). Although beyond the scope of this article, solving Eqs. (3) to (5) simultaneously [with Eq. (3) in differential form] and then applying the solutions to Eqs. (1) and (2) allows a more rigorous approach for predicting V^{CST} and C_c^{CST} with time. The rigorous approach

eliminates the need for the assumptions that $\alpha \Delta P$ is much smaller than K_C , and Q^B and Q^D are constant as demonstrated above. In many dialysis models, the assumption of negligible $\alpha \Delta P$ is always assumed.^[4,7] The rigorous approach is advantageous for students to use when the negligible $\alpha \Delta P$ assumption is not valid, providing an additional opportunity for students to compare the rigorous solution to the simplified solution to understand the error associated with assumptions.

This work presents a dialysis model that demonstrates the assessment of model assumptions. It will detail the dialysis project statement delivered to the student team, the experimental protocol, the dialysis model, experimental results, and student feedback and assessment.

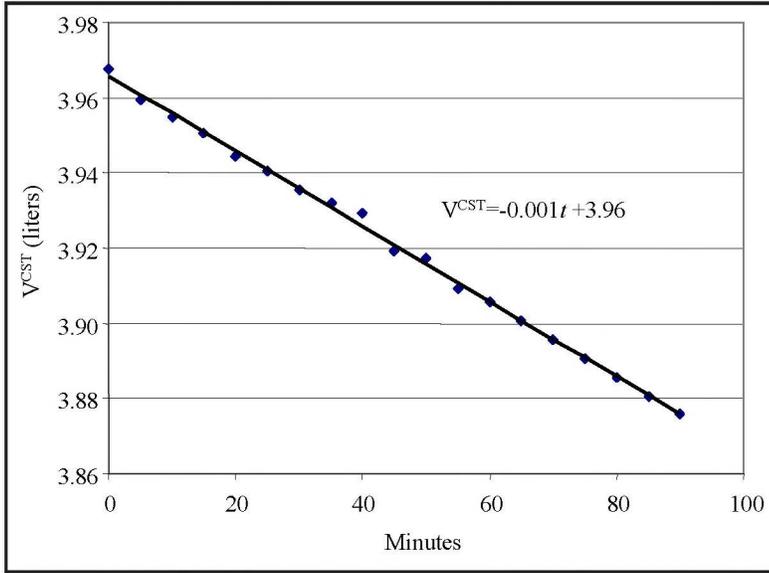


Figure 3. Volume of the “blood” (V^{CST}) as a function of time (t). Creatinine was initially present at 4.1 mM with $Q^{B,in} = 500$ ml/min. The line represents the solution to Eqs. (2) and (7), where the slope is used to evaluate K' .

In addition, the models can be further expanded to include multiple species and the utilization of species in which $\sigma \neq 0$. Thus, the dialysis project has great potential for many applications involving model development, validation of assumptions, and comparison with experimental results. Exposing students to the various levels of model development helps them learn how to simplify models using certain assumptions.

For example, blood contains proteins, salts, urea, and other metabolites. The proteins are too large to transport through the dialyzer ($\sigma = 1$ and K for protein is negligible), such that the proteins contribute to an osmotic pressure. If only proteins (P) and creatinine (C) were present, Eqs. (3) to (5) would be expanded to:

$$\frac{-dQ^B}{dA} = \frac{-dQ^D}{dA} = \alpha[\Delta P - RTC_p^B] = K' \quad (8)$$

$$\frac{dC_p^B}{dA} = K' \frac{C_p^B}{Q^B} \quad (9)$$

$$\frac{dC_c^B}{dA} = \frac{K_c}{Q^B} (C_c^D - C_c^B) \quad (10)$$

$$\frac{dC_c^D}{dA} = \frac{K_c + K'}{Q^D} [C_c^D - C_c^B] \quad (11)$$

The RTC_p^B term in Eq. (8) is the osmotic pressure contribution due to proteins. Eq. (9) is the protein material balance on the blood side that demonstrates the protein concentration can change as a result of water flow through the membrane (note that protein is not in the dialysate, so a protein balance in the dialysate is not needed). The solutions to these equations

[combined with Eqs. (1) and (2)] can be solved to provide V^{CST} and C_c^{CST} predictions with time. The value of RTC_p^B is typically 28 mmHg, and dialysis is often performed where ΔP is on the order of 200 mmHg.^[4] Thus, K' is positive leading to a decreasing Q^B along the length of the dialyzer. According to Eqs. (8) and (9), the protein concentration will increase due to the loss of water and the creatinine concentration in the blood will decrease. The model can be used to assess the degree to which increases and decreases occur. Unlike the example given in this article using creatinine alone where K' (or $\alpha\Delta P$) was assumed negligible, K' is required to assess the changes in protein concentration on the blood side (as a result of water loss) according to Eq. (9). A valuable exercise for students would be to derive Eqs. (8) through (11) and show how the equations can be solved with Eqs. (1) and (2) to predict time profiles of V^{CST} and C_c^{CST} .

EXPERIMENTAL RESULTS

Figure 3 shows a plot of V^{CST} vs. time for a closed-loop experiment in which creatinine was initially present at 4.1 mM and $Q^{B,in} = 500$ ml/min. With a negative slope of one ml/min (*i.e.*, 1 ml/min of water transports from the blood to the dialysate) and $A_M = 1.5$ m² (CL T150L, Terumo Medical Corporation, Tokyo, Japan), $\alpha\Delta P$ is 6.7×10^{-5} cm/min ($\alpha\Delta P A_M = 1$ ml/min). According to Eq. (3), $Q^{B,out} / Q^{B,in} = 0.998$. Thus, Q^B is essentially constant such that the assumption of $\alpha\Delta P A_M \ll Q^{B,in}$ is valid. Since Q^D was greater than Q^B , the assumption of $\alpha\Delta P A_M \ll Q^{D,in}$ is also valid for this particular experiment. Although ΔP was not measured at $Q^{B,in} = 500$ ml/min, $\Delta P \approx 26$ mmHg was observed at $Q^{B,in} = 300$ ml/min, leading to an approximation of $\alpha = 2.6 \times 10^{-6}$ cm min⁻¹ mmHg⁻¹.

When evaluating K_c , the open-loop experiment was performed at $Q^{B,in} = 300$ ml/min and $Q^{D,in} = 817$ ml/min with $C_c^{CST} = 3.22$ mM. The analytical measurements for this work were sensitive enough to distinguish differences between C_c^{CST} and $C_c^{B,out}$. The measured value of $C_c^{B,out}$ was 2.03 ± 0.03 mM, leading to $C_c^{B,out} = 0.63 C_c^{CST}$ and $E = 0.37$. For countercurrent flow with $z = 0.37$, Eq. (7) yielded a value of 0.5 for N_T . Thus, K_c is 0.01 cm/min, which validates the assumption that $\alpha\Delta P \ll K_c$. This value of K_c is similar to values observed for other hemodialyzers.^[7]

Once model parameters were obtained and the assumptions were validated, Eqs. (1) and (2) (with $C_c^{B,out} = C_c^{CST}$ (1-E) and $Q^{B,out} = Q^{B,in} - \alpha\Delta P A_M$) were solved simultaneously using Polymath^[8] to predict V^{CST} and C_c^{CST} with time. The predictions were compared to experimental results from a closed-loop experiment in which 2.54 mM of creatinine was initially present in 4 liters with $Q^{B,in} = 300$ ml/min and $Q^{D,in} = 865$ ml/min ($z=0.347$). From Eq. (7) with $A_M = 1.5$ m² and

A benefit of incorporating the dialysis project is that the student can integrate a number of concepts such as material balances/modeling (i.e., blood and dialysate balances with assumptions), transport issues (i.e., evaluation of transport coefficients), model validation of assumptions, and solving differential equations (i.e., using Polymath) toward a bioengineering project that allows the student to expand the scope of his/her chemical engineering education.

$K_c = 0.01$ cm/min ($N_T=0.5$), $E=0.37$. Figure 4 shows that the model results for C_c^{CST} , with $\alpha\Delta P$ ranging from 0 (constant flow assumption) to 20×10^{-5} cm/min (representing a 3-fold increase in $\alpha\Delta P$ from the experimental $\alpha\Delta P$ value), are the same. Increased water transport can occur via either increasing ΔP or adding a constituent that contributes to the osmotic pressure (where $\sigma \neq 0$). The model predictions are in general agreement with the experimental results although there is a small discrepancy. The time to remove 90% of the creatinine is 80 minutes. In all cases, varying $\alpha\Delta P$ did not affect the C_c^{CST} profile (as expected with $\alpha\Delta P \ll K_c$). After 100 minutes, however, the predicted V^{CST} was 4000 ml, 3900 ml, and 3700 ml for $\alpha\Delta P=0$, $\alpha\Delta P=6.7 \times 10^{-5}$ cm/min, and $\alpha\Delta P=20 \times 10^{-5}$ cm/min, respectively. As is evident, $\alpha\Delta P$ is critical for predicting water loss but does not affect predictions. Figure 4 also shows predictions for $\alpha\Delta P=0$ with $Q^{B,in} = 500$ ml/min ($E=0.24$). As seen, the C_c^{CST} profile does not drastically change and the time to remove 90% of the creatinine only decreases to 76 minutes.

STUDENT FEEDBACK AND ASSESSMENT

Some of the comments from students included “this experiment trained us with [nontraditional] equipment” and “I liked seeing how close a model would actually fit experimental data.” There were several indirect assessments. Students liked this project and explored more than they were asked to do in the project statement. For example, they explained the difference in various types of dialysis processes, provided statistics about each type, examined the relevance of creatinine in clinical settings, explored the importance of osmolarity, and developed an understanding for the need of electrolytes in the dialysate. While presenting their findings, they named their patient, talked about poor “Charlie” needing to sit for two hours while the dialysis was taking place, and worried about how creatinine generated in the body during dialysis would affect the creatinine removal process. To account for creatinine generation during dialysis, a constant generation of creatinine could be introduced into the experiment. It was also observed that as students were told that they could present their results at the regional and national American Institute of Chemical Engineers (AIChE) student conferences, students were more willing to spend extra time on the project. One student presented his team’s results at the 2004 Mid-America Regional

AIChE Conference and won second place.

One difficulty observed during the implementation of the dialysis project was that students tended to focus on the analysis (i.e., measurements), and focused less on the modeling aspects. For instance, students spent ample time on the creatinine analysis. One problem that was encountered, however, was that students were not used to using micropipettes and error in the calibration curve could be dominant if proper volumes were not dispensed every time. Thus, it is important to train students in using equipment that is not often associated with traditional unit operations experiments. With regards to modeling, the students did not always explore the resources for model development. It would be beneficial for the instructor to direct students toward resources containing information about model development. The main point is that students involved in nontraditional experiments should have some training or guidance (such as identification of key resources) to help them achieve their objectives.

CONCLUSIONS

Through the incorporation of creatinine dialysis, undergraduates can integrate a number of concepts such as material balances/modeling (i.e., blood and dialysate balances with

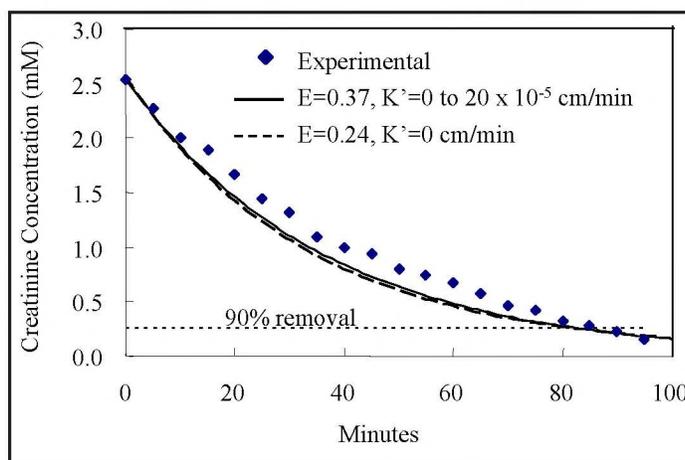


Figure 4. Creatinine concentration (initially 2.54 mM) in the continuously stirred tank (CST originally at 4000 ml) as a function of time for $Q^{B,in} = 300$ ml/min and $Q^{D,in} = 865$ ml/min. The model is the solution to Eqs. (2) and (3) with $C_c^{B,out} = C_c^{CST}$ (1-E) and $Q^{B,out} = Q^{B,in} - KA_M$. A_M is 1.5 m².

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assumptions), transport issues (*i.e.*, evaluation of K_c), model validation (*i.e.*, validating assumptions), and solving differential equations (*i.e.*, using Polymath) towards a bioengineering project that allows the student to expand the scope of his/her chemical engineering education. The students enjoyed the exposure to “nontraditional” experiments and this project provided them an opportunity to connect bioengineering experiments to material learned in the classroom. Deriving the differential equations from the continuity equation requires the student to draw on his/her math and engineering knowledge. It is important for students to assess the validity of assumptions when applying experimental results to model equations, and this project allowed for such opportunities.

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