CEE

chemical engineering education

VOLUME 44 • NUMBER 2 • SPRING 2010

Chemical Engineering Division, American Society for Engineering Education

American Institute of Chemical Engineers

Robert C. Armstrong

of MIT

Feature Articles . . .

and ChE at . . .

NC State University

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Chemical Engineering Education

Volume 44 Number 2 Spring 2010

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

Chemical Engineering at...

NC State University

LISA G. BULLARD, PETER S. FEDKIW, AND FRANCIS P. O'DELL

Much has changed in the 30 years since *CEE* last published an article, in 1979, on the chemical engineering program at North Carolina State University. That is an understatement—almost everything has changed: our name, our location, our faculty, the advent of online graduate distance learning, and departmental diversity, to name a few.

We added "Biomolecular" to our name in 2004 to reflect the broader impact of life sciences on our discipline. The same year we moved from Riddick Engineering Laboratories, a building that we occupied on the NC State main campus for 55 years, to a showcase facility on the university's new and rapidly growing Centennial Campus. We have expanded our Ph.D. graduate research program and have developed an internationally subscribed online M.S. degree program that is a model for such activity. And compared to the "old" days, we have become more diverse in faculty and students. What has remained unchanged over these 30 years is the quality of the education that our faculty provides undergraduate and graduate students.

THE UNIVERSITY, THE COLLEGE, AND THE DEPARTMENT

To many folks, the mention of North Carolina brings to mind the four seasons as experienced from the scenic Outer Banks in the east to the Appalachian Mountains in the west; sweet tea and barbecued pork; and the fierce rivalry of ACC basketball traditions among NC State, Duke, and UNC-Chapel Hill. The state is also increasingly well known for its technology focus, however, as evidenced by the renown of the Research Triangle Park; the state's investment in education; its position as a growing hub of biotechnology and biomanufacturing (currently more than 500 companies); and the international recognition that the NC State Centennial Campus has gained as a model for the promotion of university and industrial interactions and cooperation. The state's business climate has been ranked the best in the nation by *Site Selection* magazine for the fifth year in a row—and eight of the last nine years.

North Carolina State University is located in Raleigh, NC, the state capital. NC State is the largest university of the 16 campuses in the University of North Carolina system, and it receives more applications than any of the others. The university has a current enrollment of almost 25,300 undergraduate and 8,600 graduate students. The academic campus has more than doubled in size since 1979 with the opening of our Centennial Campus in 1985—which at the time consisted of 805 wooded acres within walking distance of the main campus. Centennial Campus, named to celebrate NC State's founding in 1887, is a unique environment for a university and an extraordinary success story—a research park and campus providing corporate, governmental, and nonprofit partners close proximity to world-class research facilities and a highly educated workforce, all in an amenity-rich environment (<http://centennial.ncsu.edu>).

The College of Engineering (COE) consists of 12 engineering departments that, combined, offer 18 bachelor's-, 17 master's-, and 13 doctoral-degree programs. The undergraduate enrollment is near 6,000, and graduate enrollment is approximately 2,300. The COE is among the largest engineering colleges in the nation and is commonly in the top five in the number of B.S. degrees awarded annually. We anticipate in the next few years that the College's move to Centennial Campus will be completed and the COE will join the College of Textiles as the two anchor academic units on the new Campus.

The Department of Chemical and Biomolecular Engineering (CBE) moved in 2004 to Engineering Building I on Centennial Campus, a building that we share with the Department of Materials Science and Engineering. Our department has an enrollment of about 500 undergraduates and 120 graduate students, and over the last 10 years we have averaged 95 B.S., 20 M.S., and 12 Ph.D. degrees awarded annually. Our undergraduate program is consistently in the top 10 producers of B.S. degrees, and our graduate program has reached that same milestone several times in the last 10 years.

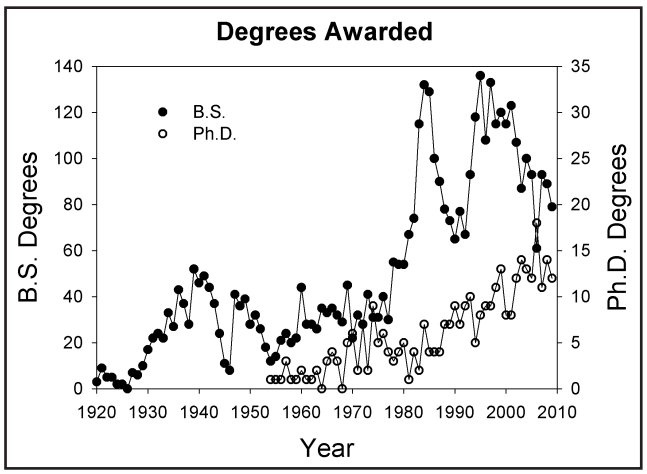


Figure 1. *Our historical production of B.S. and Ph.D. graduates.*

HISTORY

The NC State Chemical Engineering Department was formally established within the School of Engineering in 1924, but the origins of chemical engineering actually date to 1899 when a four-year program leading to the "Degree of Bachelor of Engineering" and a two-year graduate program leading to the "Degree of Chemical Engineer" were introduced. The catalog of the time for "North Carolina College of Agriculture and Mechanic Arts" (as the university was then known) described the program: "For young men seeking employment in the analytical or engineering departments of the various chemical industries such as the manufacture of soap, paper, leather, vegetable oils, glass, porcelain, illuminating gas, sulphuric acid, fertilizers, etc." The program was modified in 1902 so the six students who started in chemical engineering were eventually awarded B.S. degrees in Industrial Chemistry. Incidentally, one of these students, O. Max Gardner, later became governor of North Carolina—another testament to the (even then) breadth of education afforded to a chemical engineering student. A chemical engineering program was started once again in 1916, at which time the various engineering disciplines were administered together—separate departments did not exist. Twelve students obtained chemical engineering degrees before the department was officially created in 1924.

In 1928 the first Master's of Science in Chemical Engineering was awarded. The department received approval to establish a Ph.D. program in chemical engineering in 1949 and five years later graduated its first Ph.D., **Jim Ferrell**, who was selected in 1966 as department head after recommendation of a committee chaired by Professor **Warren L. McCabe**.

Student Demographics and Number of Degrees Awarded

Both the number of graduates and the percentage of females in the program have increased dramatically since the *CEE* profile appeared in 1979. The number of B.S. graduates in the 10 years preceding 1979 was 364, and the number over the past 10 years is 2.6 times greater, at 947. The percentage of women graduates increased from 6% in the 10 years preceding 1979, to 35% in the past 10 years. The percentage of females is still on the rise, with 47% of our 2008-09 B.S. graduates being women. Figure 1 shows our historical production of B.S. and Ph.D. graduates. Over our history, the department has conferred 4,500 B.S., 534 M.S., and 342 Ph.D. degrees.

We have a mission as a land grant institution to educate the citizens of North Carolina, but we encourage applicants and welcome students from around the country and the world. Over the last 10 years, 79% of our B.S. graduates were from North Carolina, 16% from other states, and 5% international. Over the same period, 59% of our M.S. and Ph.D. graduates were from the United States and the remaining 41% from other countries.

FACULTY

Our faculty members and the universities of their doctorate degrees are listed under the group photo, facing page.

The interdisciplinary aspects of our research and teaching interests are reflected in the appointment of two faculty members from other NC State colleges (Flickinger, of Agriculture and Life Sciences, and Pourdeyhimi, of Textiles) with associate faculty member status, as well as the appointment of the first faculty member in the UNC system to have full faculty status at two institutions (DeSimone, joint with Chemistry UNC Chapel Hill). In addition, we are pleased to include a number of adjunct and research faculty who are listed at our department Web site along with the staff who underpin our enterprise (<www.che.ncsu.edu>).

We are proud of the accomplishments of our faculty and the recognitions that they have received. Among these achievements, we are pleased that three of our faculty are members of the National Academy of Engineering (DeSimone, Gubbins, and Hall); 12 faculty members are Fellows of professional societies (Carbonell, DeSimone, Fedkiw, Felder, Flickinger, Genzer, Gubbins, Hall, Kelly, Parsons, Spontak, and Westmoreland); and eight faculty members are NSF CAREER award winners (Dickey, Genzer, Haugh, Lamb, Peretti, Parsons, Velev, and Westmoreland). In addition to numerous awards at the national, regional, and local level from the AIChE, ACS, ASEE, and other professional societies or organizations, we are pleased that three of our faculty (DeSimone, Gubbins, and Hall) were recognized in the 2009 AIChE Centennial celebration as members of the "100 Chemical Engineers of the Modern Era," and that the list of groundbreaking chemical engineering texts in the discipline included one co-authored by Felder.

TEACHING IS IMPORTANT

Our department places particular emphasis on teaching effectiveness. Twelve of our faculty members have won University-wide Alumni Association teaching awards. Rich Felder, Dave Ollis, and Lisa Bullard are especially well known in the profession for their contributions to chemical engineering education. Our department won the inaugural NC State University "Departmental Award for Teaching and Learning Excellence," an indication of how well we are respected by our university peers.

Perhaps our department is most well known as the birthplace of the best-selling chemical engineering textbook, *Elementary Principles of Chemical Processes* by Rich Felder and Ron Rousseau (who was at NC State when the book was written and is now chair at Georgia Tech). This book is used at more than 80% of chemical engineering departments in the United States and has been translated into seven languages. Rich and his wife and colleague, Rebecca Brent, have brought international recognition to NC State as a result of the more than 300 teaching-effectiveness workshops they have given around the world, including the National Effective Teaching Institute offered annually at ASEE meetings since 1991.

Other textbooks written by NC State faculty include *Chemical Reactions and Chemical Reactors* (George Roberts), *Biochemical Engineering Fundamentals* [David Ollis (NCSU) and James Bailey], and *Unit Operations of Chemical Engineering* [Warren McCabe (NCSU) and Julian Smith].

UNDERGRADUATE PROGRAM

Curriculum

Out of 125 credit hours required for the B.S. degree, our undergraduate students take 12 core courses in chemical engineering and six in chemistry. In addition to a core chemical engineering program, the B.S. students may enroll in one of five concentration areas that reflect the research interests of our faculty and the types of industrial positions that our graduates may pursue:

- ***Biomanufacturing Concentration*** *– The biomanufacturing concentration provides students with the knowledge base and hands-on skills to prepare them to quickly contribute to a cGMP (current good manufacturing practice) biomanufacturing operation.*
- ***Biomolecular Concentration*** *– The biomolecular concentration integrates a unique set of core and advanced bioscience course offerings that are relevant to the pharmaceutical, medical, and agricultural fields.*
- ***Honors Program*** *– The honors program allows talented students to gain a deeper understanding of chemical engineering principles in preparation for graduate study. Honors versions of core coursework, an advanced math elective, a graduate CHE course, and an honors thesis are required.*
- ***Nanoscience Concentration*** *– The nanoscience concentration allows students to develop an understanding of the scientific and technological principles associated with the design and manufacture of patterns and devices with features and advanced functionality on the nanometer scale.*
- ***Sustainability, Energy, and the Environment Concentration*** *– This concentration involves the study of critical environmental issues in product design, process development, and research on industrial and energy systems.*

Undergraduates' Careers

Our B.S. graduates begin their careers in a wide variety of industries. Figure 2 shows the initial placement of our graduates over the last 10 years. Although many of them accept their initial position in the Southeast United States, they are eventually located across the country and the world. Almost one-quarter of our B.S. graduates immediately enter a graduate program in engineering, law school, medical school,

Faculty members of CBE at 2009 retreat (not listed in order of appearance).

Kenneth Beatty, *Michigan*, Emeritus

Chase Beisel, *Cal Tech* (starting 2011)

Lisa Bullard, *Carnegie Mellon*,
Director of Undergraduate Studies

Ruben Carbonell, *Princeton*

Joseph DeSimone, *VA Tech*

Michael Dickey, *UT Austin*

Peter Fedkiw, *Cal Berkeley*,
Department Head

Richard Felder, *Princeton*, Emeritus

Michael Flickinger, *Wisconsin*

Jan Genzer, *Pennsylvania*,
Associate Department Head

Christine Grant, *Georgia Tech*,
Associate Dean of Faculty Development and Special Initiatives, College of Engineering

Keith Gubbins, *Kings College, University of London*

Carol Hall, *Stony Brook*

Jason Haugh, *MIT*

Wesley Henderson, *Minnesota*

Harold Hopfenberg, *MIT*, Emeritus

Robert Kelly, *NC State*

Saad Khan, *MIT*,
Director of Graduate Studies

Henry Lamb, *Delaware*

P.K. Lim, *Illinois*

David Ollis, *Stanford*

Gregory Parsons, *NC State*

Steven Peretti, *Cal Tech*

Behnam Pourdeyhimi, *Leeds*

Balaji Rao, *MIT*

Gregory Reeves, *Princeton*

George Roberts, *MIT*, Emeritus

Richard Spontak, *Cal Berkeley*

Orlin Velev, *University of Sofia*

Phillip Westmoreland, *MIT*

Hubert Winston, *NC State*, Emeritus

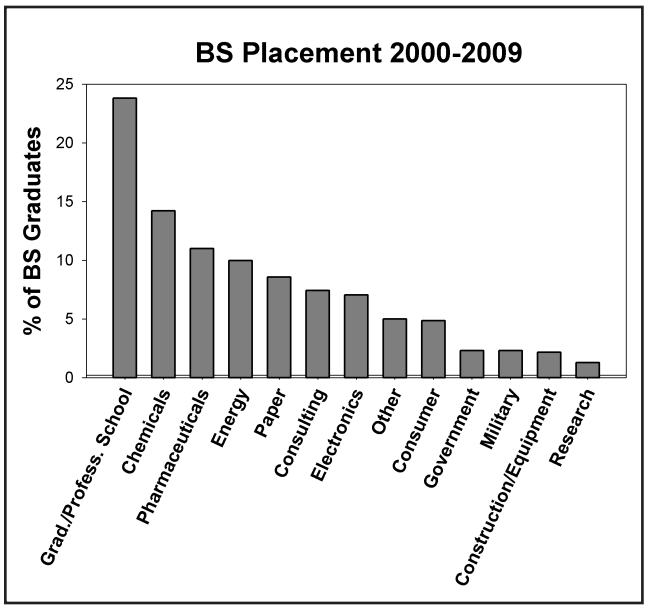


Figure 2. *The initial placement of our undergraduates over the last 10 years.*

dental school, business school, or pharmacy school. Selected achievements of our graduates include: presidents and CEOs of Fortune 500 corporations; company owners and entrepreneurs; membership in the National Academy of Engineering; military leaders, including a four-star general; leadership positions in academia; renowned M.D.s and surgeons; and court judges, among others.

STUDENT ORGANIZATIONS

Our AIChE student chapter was the 15th chapter established in the United States and the first in the South, and has been in place continuously since 1930. It has won a national student chapter of the year award 14 times in the past 20 years. Our students have been instrumental in establishing student chapters of the International Society of Pharmaceutical Engineers in 1996 and Omega Chi Epsilon in 1997, and many are active in the Society of Women Engineers, National Society of Black Engineers, Society of Hispanic Professional Engineers, and Engineers Without Borders. Our graduate students have had a Graduate Student Association (GSA) chapter since the 1970s (its organizer and first president was **Francis O'Dell**, now the department's director of development). The GSA plays an active role in the social fabric of the department and is instrumental in our annual recruiting efforts of first-year graduate students.

GRADUATE PROGRAM

We offer two thesis degrees: the Doctor of Philosophy (Ph.D.) and the Master of Science (M.S.). The emphasis, however, is on the Ph.D. program, with 95% of our graduate students being part of it. A unique aspect of our doctoral program is the replacement of the traditional written qualifying examination with a research proposition—a change that we implemented 18 years ago and was described by Ollis elsewhere (*CEE*, 222-29, Fall 1995). The research proposition has evolved into a pair of research-related courses taken by students during their first year and consists of Introduction to Research during the Fall semester and the Research Proposition course in the Spring. We offer these two novel courses to better prepare students to function at high levels of productivity in both their Ph.D. studies and careers, and to teach the mechanics of effectively communicating to a technical audience through proposals (hypotheses) and papers (results). In the Introduction to Research course, the student independently develops an original chemical engineering research paper and defends it orally to the course instructor. The class also covers issues related to research ethics. In the follow-on Research Proposition course, the student creates an NSF-format-like proposal, typically in the area of his/her anticipated Ph.D. study, under the guidance of the course instructor and thesis advisor, and defends it before a faculty committee. Successful completion of these two courses and four core first-year graduate courses qualifies the student to continue for the Ph.D.

Creativity, collaboration, and innovation are characteristics emphasized and nurtured in our research programs, which encompass a variety of aspects of chemical and biomolecular engineering. Fundamental studies include investigating nanoscale phenomena, reaction pathways in living cells, protein purification, thin-film dynamics, and polymer physics. More applied topics include fabricating functional nanostructures and nanoelectronic devices, using microfluidic systems, and developing alternative sources of clean energy, to name a few. Following are the present areas of research strength in the department and the faculty members involved with them:

- ***Biofuels and Renewable Energy Technology:*** *Dickey, Fedkiw, Henderson, Khan, Lamb, Parsons, Peretti, and Westmoreland*
- ***Biomolecular Engineering and Biotechnology:*** *Beisel, DeSimone, Carbonell, Hall, Haugh, Kelly, Rao, and Reeves*
- ***Catalysis, Combustion, Kinetics and Electrochemical Engineering:*** *Fedkiw, Lamb, and Westmoreland*
- ***Computational Nanoscience and Biology:*** *Gubbins, Hall, and Westmoreland*
- ***Environmental Studies:*** *Grant, Ollis, and Peretti*
- ***Nanoscience and Nano-Engineering:*** *DeSimone, Dickey, Genzer, Khan, Parsons, and Velev*
- ***Polymers:*** *DeSimone, Dickey, Genzer, Hall, Khan, and Spontak*

Graduates' Careers

Figure 3 shows the initial placement of our Ph.D. graduates over the last 10 years. The majority of them continued their studies in post-doctoral research positions at other institu-

tions. Over the 17-year period from 1953-1980, 17 of our Ph.D. students went into academia, while 31 have done so from 1981 through 2009.

Distance Master of Science Degree

The department was a pioneer in establishing a distance-education-based Master of Science in Chemical Engineering program, which originally began with videotapes that were distributed through the mail and has evolved to delivery of content through online streaming video. Students in the program come from all over the United States and abroad. The distance program provides an opportunity for individuals in the work force to complete their studies while maintaining full employment, and also for non-chemical engineers to train themselves to be chemical engineers. This non-thesis M.S. in chemical engineering is a 30-credit-hour program that offers Web access to all core graduate classes and most CBE graduate electives. To earn the degree students must take at least 10 three-hour courses with at least seven being in chemical engineering.

BIOMANUFACTURING TRAINING AND EDUCATION CENTER

The Golden LEAF Biomanufacturing Training and Education Center (BTEC) opened on Centennial Campus in 2007. BTEC simulates a biomanufacturing facility capable of producing sterile bulk biopharmaceutical compounds, and the building includes classrooms, laboratories, and high-purity building and process utilities. The facility delivers a "hands-on" educational experience for all levels of post-secondary students and does so using large-scale, state-of-the-art equipment and process systems in a cGMP environment. This unique facility is the first of its kind in the country and one of only a few in the world. BTEC was founded under the leadership of our former department head, Peter Kilpatrick (now dean of engineering at Notre Dame), and its present director is also a former CBE department head, Ruben Carbonell. Our undergraduate students in the biomanufacturing concentration take BTEC classes and graduate students perform research under the guidance of CBE faculty who participate in BTEC's mission.

OTHER FACULTY INTERESTS

While our faculty members maintain very high standards in both their teaching and their research, they also enjoy diverse personal interests and all contribute immensely to creating a collegial environment.

Since retiring as the ace pitcher on the graduate student softball team, Peter Fedkiw has become an avid fan of NHL hockey and is a season ticket holder of Raleigh's Carolina Hurricanes (as well as the Broadway South stage series). Sporting his "Lord of the Rings" jacket, Rich Spontak is our local Tolkien aficionado. Rich is an avid writer (he has a poem

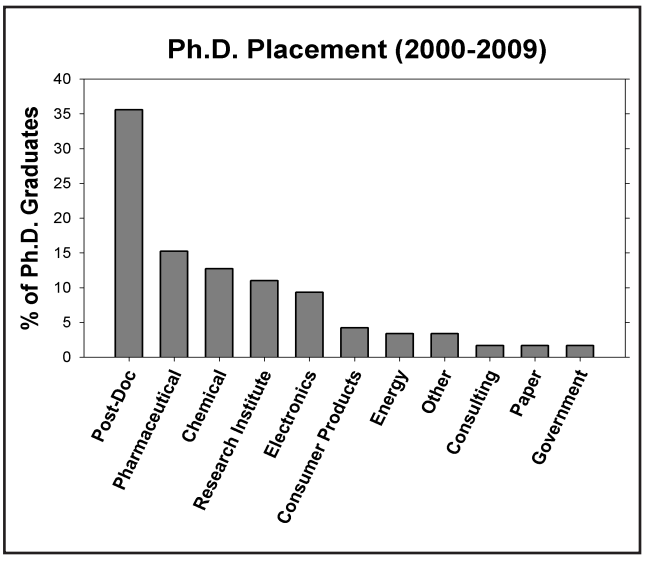


Figure 3. *The initial placement of our Ph.D. graduates over the last 10 years.*

entered in the U.S. Congressional Record) and likes to coach teenagers in Odyssey of the Mind and Math Counts, as well as playing chess and squash. Carol Hall is a ballroom-dance enthusiast and participates in regional competitions. In the summer, she can often be seen paddling her yellow kayak on local lakes. Christine Grant treasures the time that she spends working to support women's ministries at her church. One of her dreams is to work on the set of a movie as a special-effects engineer.

Orlin Velev relaxes by traveling with his family and often schedules intense programs of sightseeing and cultural events on such trips. At home Orlin enjoys watching movies; he's keen on documentaries on history, especially those featuring events of the Cold War. Several faculty members are musicians: Jason Haugh is a capable guitarist/multi-instrumentalist and songwriter; Chase Beisel is a drummer who's played in diverse musical groups ranging from concert bands to a college drumline; Rich Felder plays classical guitar; Jan Genzer played piano for about a decade as a youngster (about a century ago, he jokes) and still finds amusement and inspiration in "teasing" the keyboard; Steve Peretti is a Gilbert and Sullivan aficionado who has performed with the Durham Savoyards; and Lisa Bullard sings in the praise team at her church. Hubert Winston practices tai chi and qi gong—energy techniques based in Chinese medicine—and has also served as a mediator in local small claims court.

Jan Genzer, Jason Haugh, and Chase Beisel are unabashed beer enthusiasts (and quite picky about what they drink). When not trying to keep up with his four teenagers and their activities, Henry Lamb still plays basketball a few times a week, goes horseback riding, and tends to his various critters (horses, dogs, and cats). He enjoys camping and hiking—especially in the NC mountains and the western United States. P.K. Lim has

also made recent visits to the western United States and is unafraid to set off on cross-country road trips with his three small children in tow. Jan Genzer is a talented mimic who can wittily impersonate graduate students and faculty members. Bala Rao reads books on economics in his spare time, while Dave Ollis is the man to see if you ever want to learn about the history of porcelain or re-discover ancient technology of China. Dave is also often accompanied by "Teddy," a lovable pound hound who whiles away most days sleeping on the Oriental rug in Dave's office and getting treats from the staff (and getting much attention from just about any visitor who passes by Dave's office during the day). No wonder Teddy has become the unofficial departmental mascot! Joe DeSimone is a fierce fan of all teams Philadelphia and recently attended, with his son, Game 4 of the World Series in Philadelphia against the NY Yankees. Joe enjoys playing tennis and riding bikes on Holden Beach with his family.

Greg Parsons coaches his daughter's soccer team, and Bob Kelly coached his son's baseball team. Bob is also a big Mets and Giants fan. Saad Khan whips up a mean curry (besides picking up occasional takeout from Burger King). Wesley Henderson regales the students with tales from his days as an Airborne Ranger parachuting out of planes in the first Gulf War; his claim to cinematic fame is that he was an extra in the movie "Outbreak." Michael Dickey is a rabid Wolfpack sports fan who has been known to chase down football or basketball coaches to get a photo taken with them. This phenomenon has been witnessed by several faculty members who are willing to confirm it in court if necessary. Greg Reeves likes to swim and play water polo, and is a big fan of Atlanta Braves baseball as well as college football. Greg also likes to ponder the big questions in life and is an active participant in his church ministries. Hal Hopfenberg, in addition to being a famous local gourmet cook and our former department head, has the distinction of having been athletic director of NC State. When he was appointed, the newspapers winked that his previous athletic experience had been on the basketball team at MIT, but in the end he pulled the athletic program through a difficult time. Michael Flickinger is an amateur architect and a lifelong house carpenter, hand woodworker, and furniture designer who donates his carpentry time providing safe, warm, dry, and affordable housing locally and in Appalachia. When he's not gardening with his wife, or working in his shop, you can find Michael tending his small flock (no, not his lab group, but his heritage chicken breeds) which provides his family, students and colleagues with fresh eggs every week.

Keith Gubbins, besides being known as a snappy dresser, enjoys bird watching, swimming laps, and boating. Keith owns an extensive art collection. Ruben Carbonell recently obtained his Captain's license from the U.S. Coast Guard (100-ton vessels, 100 miles offshore) and has charter cruises planned to the West Coast of Florida (Sanibel, Useppa, Marco Islands), the San Juan Islands in the state of Washington, and the Turks and Caicos in the Caribbean. Ruben likes to dance to Cuban music and cook Cuban food, and he is the only faculty member who has had three children graduate from NC State, one from the department—luckily for both, Ruben never had him in class. George Roberts enjoys reading non-fiction about the Civil War as well as visiting Civil War battlefields and museums. For proof, check out Problem 7-7 in *Chemical Reactions and Chemical Reactors*, his recent book published by Wiley. George is also the local faculty expert on American movie classics and is infamous for telling "Pat and Mike" jokes at departmental events with a rollicking Irish accent. Rich Felder enjoys listening to music (mostly classical and opera, some jazz and folk and bluegrass and '60s and '70s rock); tacking vacations onto the international trips he takes to give teaching workshops with his wife Rebecca, doing the Sunday *New York Times* crossword, and above all, playing with his seven grandkids. Newcomer Phil Westmoreland has found the Triangle to be an amazingly hip part of the country—a blend of grassroots and the very sophisticated—and enjoys cuisine from barbecue to vegan, music from Piedmont Blues to the Cats Cradle, crafts and art, and hiking trails in the Eno River and Umstead State Parks.

* * *

We hope this description gives an idea of who we are and what we do. We also hope that it conveys the great collegiality and friendship we enjoy in our department. Not only do we have fun, we also work together well, as evidenced by nearly 40% of our graduate students being co-advised by more than one faculty member in our department. The fact that five current faculty who received their ChE degrees at NC State eventually returned to the department to teach and carry out their scholarship reflects the sense of family that extends to our students and graduates. ❐

Robert C. Armstrong of MIT

photo/Webb Chappell

Robert C. Armstrong at MIT's Chemical Engineering Department.

By Kenneth A. Smith,
Massachusetts Institute of Technology
And Sarah H. Wright

Yesterday's good answer is today's great question. That's what Bob Armstrong of MIT tells his ChemE students. Whether it's a textbook problem in fluid mechanics or a global problem in carbon emissions, answers are the best place to start asking, "What were their methods?" "How can we account for the unexpected?" "Where can we go from here?"

The Chevron professor of chemical engineering at MIT and winner of the field's most prestigious awards, Bob has been at the forefront of polymer fluid dynamics and transport phenomena for more than 30 years. In 2009 he was elected a member of the Board of Directors of the American Institute of Chemical Engineers (AIChE), and he has held a leadership role in addressing the world's energy problems, serving as deputy director of the MIT Energy Initiative (MITEI) since 2006.

A native of Baton Rouge, Louisiana, Bob grew up immersed in the new technologies that were responding to America's needs for materials and energy. Innovations in the chemical, petroleum, shipping, and other industries were burgeoning. With its port on the Mississippi and its relative safety from hurricanes and floods, the state's capital city embodied America's post-war boom.

Esso (now Exxon) and Shell had great jobs for chemical engineers—Bob's father, Wallace, worked for Ethyl Corporation, a major chemical company, throughout his career. Cars, malls, and homes hummed with air conditioning. In 1960, when Bob was 12, crude oil cost $3.00 a barrel. Gasoline was 31 cents a gallon. "I took energy for granted for most of my life," Bob says.

The energy crisis Bob now works to resolve took root in 1960, too. In a move that attracted little attention at the time, Iran, Iraq, Kuwait, Saudi Arabia, and Venezuela formed the Organization of Petroleum Exporting Countries (OPEC). American energy consumption and dependence on foreign oil would affect global industries, economies, politics, and energy supplies in years to come.

Like most Americans, Bob's personal life was more affected by events in the United States than by OPEC or the Middle East. The Vietnam War coincided with his high school and college years—in the 1969 draft lottery, Bob's number was 308. His family, active in church and civic life, were known in Baton Rouge as inclusive and pro-integration. His parents, Wallace and Eileen, received wide local recognition for their community service.

"As a youngster, I benefited from a culture of successful engineers and growing industries. My family was very service-oriented. I look on what I do today as service, as giving back to society," Bob says.

A gifted and serious student, Bob focused closely on school. In summertime, he played tennis and golf and water- and shoe-skied on Louisiana's Amite River and on Lake Maurepas, near Baton Rouge. "You had to hold those short skis just so," he says. "I got pretty good at it."

When he headed off to Georgia Tech in 1966, he already knew he would major in chemical engineering. "It was a great way to combine the subjects I liked best—math, physics, and chemistry," he says.

But don't let Bob's modesty and studious demeanor mislead you. He has a lively wit and love of adventure, warns Debbie Armstrong, Bob's wife of 40 years and also a Baton Rouge native.

"Bob found out he loved math when he got sent to detention and met the math teacher. He and a friend once blew up a shack in a bad chemistry experiment," she recalls. "When we were in high school, he was a great lab partner. At the same time, he was a drummer in a rock group—The Capers—that featured him playing solo drums in 'Wipe Out!' "

GEORGIA TECH

When he got to Atlanta, Bob was pleasantly surprised to discover a familial aspect of the chemical engineering community: Tech ChemE professor Jesse Mason had taught Bob's father at the University of Florida. "That's one of many connections I had with my father," Bob says. "And I had a similar experience at MIT: I taught the daughter of two of my former ChemE students."

Characteristically, Bob devoted his college years to academics. He kept up his musical life, too, playing snare drum for the Georgia Tech Marching Band's half-time shows at football games. "That was big-time sports—uniforms, full stadiums, TV coverage. The Yellow Jackets even went to the Orange Bowl," he says.

The Capers' rockin' drummer.

With typical understatement, Bob says he did alright at Georgia Tech—meaning, he earned A's in all his courses; passed the grueling Tech swimming test with its bizarre requirement that students swim hog-tied for one hour; and drummed for the band. He did get one F, in track. "I had no endurance for distances," he reports.

He spent his college summers working in the energy industry, working for the Gulf South Research Institute; Kaiser Aluminum; Ethyl Corporation, now the Albemarle Group; and at Esso Production Research (now Exxon) in Houston, where he studied bottom-hole samples to discern how much oil was left in the ground after initial production.

His other experiences with oil production were more the sportsman's. Bob and his family enjoyed fishing for red snapper off the Gulf Coast, boating from Grand Isle or Empire out to offshore drilling platforms. "It was great. Fish just love those platforms," he says.

THE ICY NORTH

Bob and Debbie married in August 1969. A year later, they packed their blue 1970 Chevrolet Monte Carlo, a graduation gift from Bob's parents, loaded their U-Haul trailer, and drove from Houston to the University of Wisconsin, Madison. Their destination, renowned as an epicenter of the student anti-war and environmental movements, would have felt far more foreign had not a "catastrophe quieted everything down," Bob recalls.

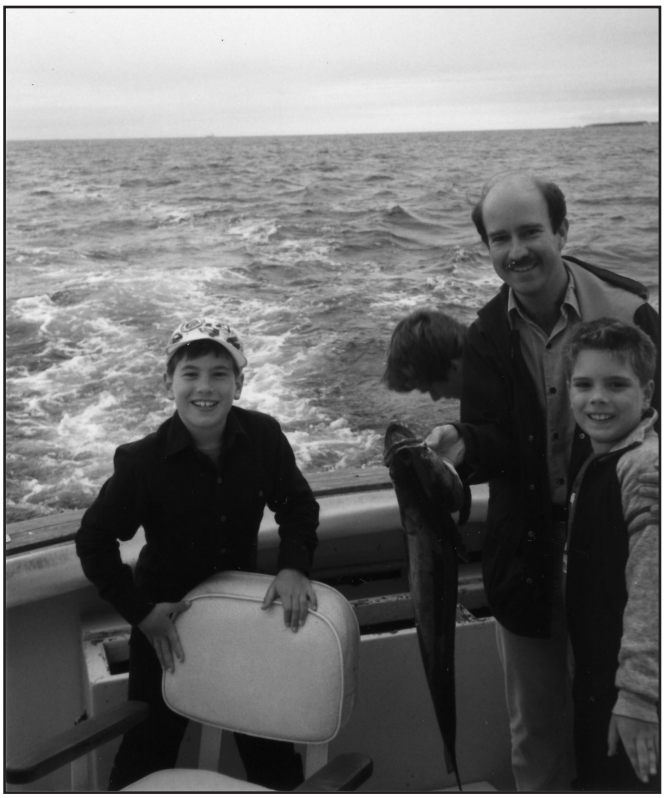
Bob and Debbie's wedding, August 1969.

"Protestors had bombed the Army Math Research Center, killing one and injuring others, two days before we arrived. Marches and demonstrations had stopped. It wasn't so different from Baton Rouge."

In their first northern winter, the newlyweds came to love Madison's frozen lakes—once they learned how to stay warm. "What do Louisianans know about cold? One morning, we woke up to find it was minus 27 degrees outside. The paint had literally fallen off our car," Bob says.

According to Professor Emeritus Robert B. Bird of Wisconsin's Chemical and Biological Engineering Department, Bob's graduate career got off to a slow start. In Bird's course on applied mathematics in chemical engineering, the new student looked "rather sleepy. But I soon learned that I could depend on him to come up with correct results."

In 1968, Bird had shifted the aims of his research program from a purely continuum approach to polymer fluid dynamics to a molecular approach. "Bob Armstrong and Ole Hassager, now ChemE professor at the Technical University of Denmark, were among the first students to tackle this very difficult and challenging field. In a sense, the three of us grew up together in a new field," he says.



Fishing with sons David and Eric.

Bob completed his Ph.D. thesis, *Obtaining Constitutive Equations from Molecular Models*, in 1973. Debbie typed it on a Smith-Corona typewriter while Bob hand-drew the equations. Just before that was done, he and Hassager proposed an astonishing project, Bird recalls.

"The two came into my office with rather odd grins on their faces. They told me, 'We'd like to write a book with you.' I had a set of very rough notes for my classes, and they wanted to volunteer to turn the notes into a book. It would involve an immense amount of work, but they did not appear to be dismayed," he says.

Bird knew whereof he spoke. He is co-author of the 780-page *Transport Phenomena* (1960) and the 1,200-page *Molecular Theory of Gases and Liquids* (1954), known around ChemE as the "Green Monster."

Undaunted, the three roughed out an outline for *Dynamics of Polymeric Liquids* ("DPL" to its fans), the first textbook on the subject, which was published in 1977. DPL's second edition appeared in 1987 and was named a Citation Classic in 1988 in recognition of how frequently it is cited in papers and books. It remains in print today. Significantly, the authors have remained close, Bird notes.

"Book-writing is a very severe test of personal relations. There were heated discussions and technical disagreements. Bob was invariably pleasant and easy to work with," says his advisor-turned-colleague.

ON TO MIT

In 1973, Bob accepted an assistant professorship in chemical engineering at MIT, where in 1888 the nation's first four-year chemical engineering program had been founded.

He and Debbie, now a clinical social worker, moved to the land of the Red Sox and the New England Patriots, settling in Lexington, Mass., a community known for its green space, good schools, and youth sports programs. Their son David was born in 1976; son Eric, in 1979. Over the next 10 years, Bob's growing leadership skills, his love of sports, and his family's example of community service would take him out to the ball game as a Little League coach and, later, president of the local league.

Eric caught baseball fever early, playing center field on a varsity team in high school and in Division One baseball at Lafayette College in Pennsylvania. His parents were in the stands for many of his AAU and college games.

Now a U.S. Marine Corps pilot, Eric was deployed in Iraq in summer 2008, and he headed out with the 24th Marine Expeditionary Unit at the beginning of 2010. "Eric loves adventure and the outdoors. His patriotism led him to enlist after 9/11," Debbie says.

According to Debbie, teaching and research in chemical engineering sometimes inspired Bob's parenting in funny, creative ways.

"When the boys were little, Bob would talk to them about how gunky and gooey materials worked. He'd illustrate by sculpting with peanut butter and squirting toothpaste out of the tube," she says.

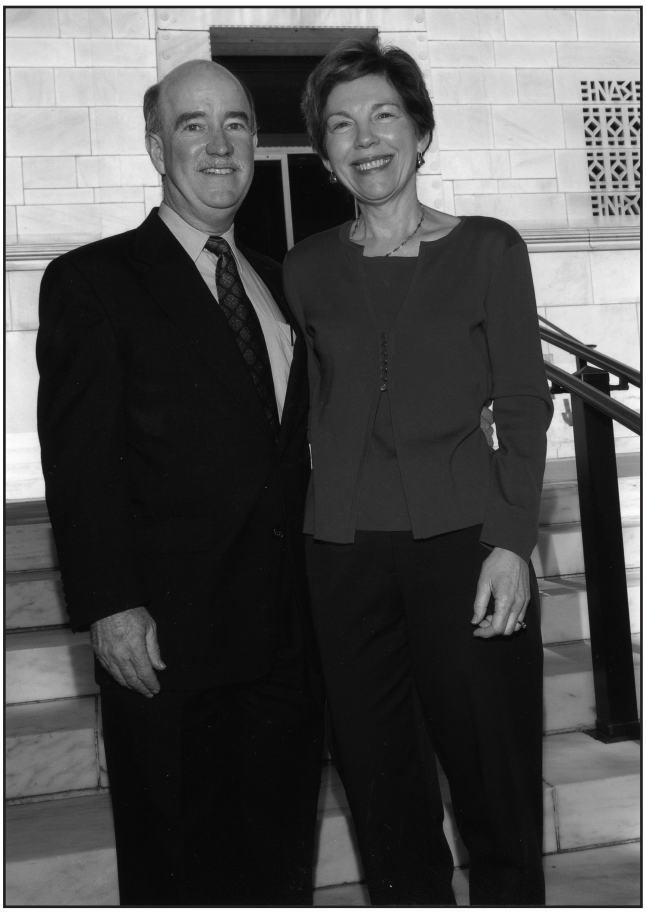
Bob recalls with amusement, "They had an action figure called Stretch Armstrong. His superpower was super-stretchable arms—a great example of viscoelasticity!"

In conversation, Bob readily cites ordinary household products—shampoo, ketchup, mayonnaise—as examples of complex fluids. He nimbly uses whatever is at hand—a pen, a glass of water, and a little polymer—to show how a non-Newtonian fluid can be lifted out of the glass with the pen. Try that with water!

"Sometimes I connect what the students are seeing to history," Bob says of his ChemE lecture style. "I tell them, this isn't new: The Roman historian Tacitus described the same mechanics. When they harvested bitumen, a tarry substance, they found it would siphon itself into a boat—very different than water."

A GIFT FOR TEACHING

Knowledgeable and enthusiastic, Bob shone as a new teacher. During his first three years at MIT, he won the Outstanding Faculty Award in 1976 and the DuPont Young Faculty Award for 1974-75 and 1975-76.



Bob and Debbie, 2009.

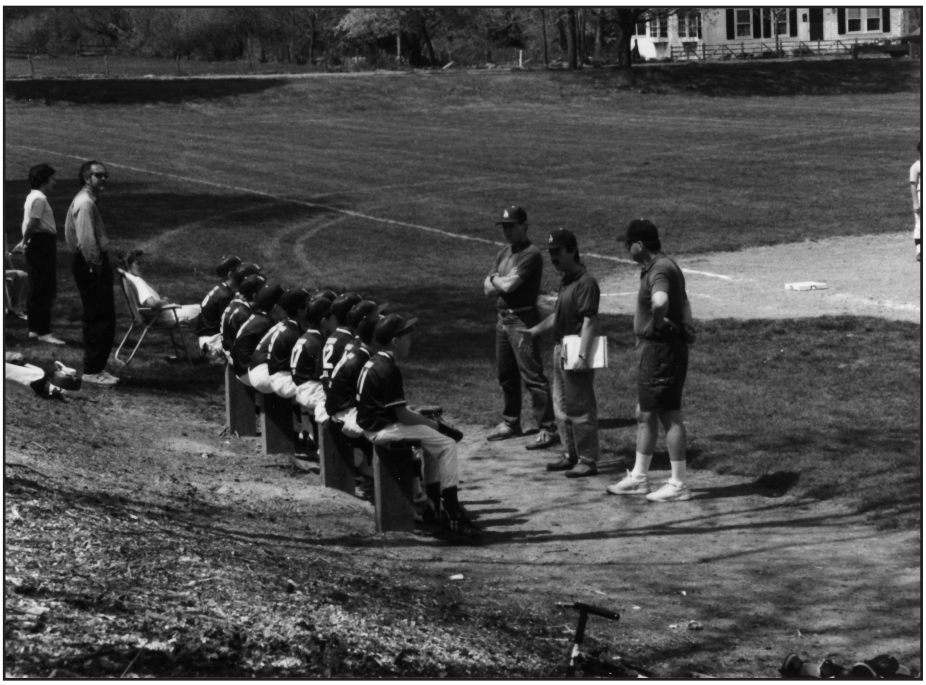
Former student Zubair Anwar (MIT Ph.D. 2008) is an associate at McKinsey & Co. In his graduate classes on transport phenomena and dynamics of polymeric fluids, "Bob often stressed that most analysis was a departure from known analytic solutions. He encouraged us to propose an answer and test its validity with fundamental equations," Anwar recalls.

Antony Beris (MIT Ph.D. 1985), professor of chemical engineering at the University of Delaware, says Bob "inspired us to give our best."

More than inspiring students to do their best, Bob has sometimes inspired students to do things they'd never considered—like include a trip to a balloon festival on a research consultation visit.

Beris had gone to meet with Bob, who was working at Exxon Corporate Research in New Jersey. "He included me with his family at the festival. He was very cordial and open with his graduate students. He gave me confidence to pursue an academic career on my own."

Promoted to full professor of chemical engineering in 1988, Bob continued to publish research in the journals of *Rheology* and of *Non-Newtonian Fluid Mechanics* (among others),



Little League Coach Bob, with clipboard.

teach, serve as a respected and demanding thesis advisor—*and* show up for Little League games.

Micah Green (MIT Ph.D. 2007) guesses it's Bob's sense of humor that helps him balance it all. "He has a corny joke chambered for any occasion. Once he told a huge audience of professors and alumni a groan-worthy joke about a duck buying Chapstick at a store and telling the cashier to 'put it on his bill'," says Green, now assistant ChemE professor at Texas Tech.

Susan Muller (MIT Ph.D. 1986) is professor of chemical engineering and associate dean, Graduate Division, at the University of California, Berkeley. Bob, one of her thesis advisors, was "a great classroom instructor. As a research advisor, he was incredibly patient and generous with his time. I'm not sure I am as patient with my students, but I think of that experience as a touchstone," she says.

In 1992, Bob won the prestigious Professional Progress Award for Outstanding Progress in Chemical Engineering, a prize recognizing significant contributions to the science of chemical engineering through discovery, invention, or service to the field.

Outside of ChemE, Bob's spirit of discovery is replenished today, as it was when he went fishing around those Gulf Coast drilling platforms, by time and activity outdoors, preferably wilderness areas.

"I dream of hiking," he says. "Debbie and I have climbed half of Mount Desert Island's 26 mountains. Beautiful scenery, vistas of ocean and other mountains, followed by popovers and tea—that's hardly roughing it. It's my favorite place."

One of Bob's memorable outdoor adventures took place in 1993, when he and his son David joined Bob Bird and John Wiest (currently Associate Dean of Engineering at the University of Alabama) for a two-week canoe trip in Quetico Provincial Park in western Ontario, Canada. "We had a great trip, but the weather didn't cooperate," Bird says. "Once, it poured all day, and we had several difficult portages. Bob held up quite well as an outdoorsman."

David held up best of all, his father and Bird recall. "Our worst day—a mile-long portage in the rain—was his favorite," Bob says. "He liked that strenuous challenge."

Later, Bob tried to return his advisor's favor by taking him on a climbing trip to New Hampshire's Mount Monadnock. Sleet and snow above the tree line defeated them before they reached the summit; both men describe the cold, thwarted hike as "interesting," like an experiment that goes awry yet opens vistas for new work.

You might say Bob hikes as he teaches. He's well prepared, enthusiastic, a good map in hand—and open to surprises.

FROM TEACHER TO LEADER

In 1996, Bob was named head of MIT's department of chemical engineering; he served in that role until 2007. As department head, Bob focused on, well, everything—teaching, research, and leadership. Yet he maintained his naturalist's ability to take in a wide landscape—the big picture—while managing challenges and change.

In the late 1990s, exciting developments in materials science and in biology raised significant questions for Bob as an academic leader. How could the department engage in these new disciplines yet retain its focus? More broadly, how could the field expand to include new areas and retain its professional identity?

These new questions called for both patience and innovation. Bob's leadership of the department included hiring 11 MIT ChemE faculty and introducing a new undergraduate program, Course 10-B, Chemical-Biological Engineering. This has proven to be a magnet for undergraduates: just over half of the department's undergraduates are now enrolled in it.

Bob's vision and commitment to ChemE education extended beyond MIT's Infinite Corridor onto the national scene when he became department head.

Thesis advisor and fellow outdoorsman Bob Bird of the University of Wisconsin, Madison, left, with Bob.

Active in discussions about the profession's identity and how it should evolve, he led one study on the subject that was funded by the NSF, and he was prominent in AIChE deliberations on the topic. In 2006, these culminated in his publishing, as sole author, "A Vision of the Chemical Engineering Curriculum of the Future" in *Chemical Engineering Education* and a chapter by the same name in *Chemical Engineering: Visions of the World*, which was published in both English and Chinese.

During his first year in administration, Bob traveled widely on behalf of the field. More than 25 speaking engagements took him to universities in Britain and Canada and across the United States; to industries including General Electric, Eastman Kodak, and Dupont; and to national conferences of the AIChE and the Society of Rheology.

OLD SCHOOL TIES, NEW GLOBAL TASKS

Back in Georgia, the Rambling Wrecks kept track as Bob's career advanced, naming him to the Georgia Tech Academy of Distinguished Engineering Alumni in 1996.

It had been 30 years since he arrived at the Atlanta campus, eager to get down to work. He enjoyed success as a professor, researcher, administrator, husband, and father. College-sports-wise, he had switched loyalties: The Wrecks' former Marching Band drummer now roots for LSU baseball and football teams, along with his Baton Rouge family and friends.

Plus, he'd erased that pesky F in track. "Right after I defended my thesis, I took up jogging and long-distance running as a hobby. Five or six miles became easy," he says.

Today, Bob keeps fit by working out four or five times a week, doing his own landscaping and gardening at home, and walking with Josie, the family's black Lab. (They also have a cat, MidKnight.)

In 1999, the drum set came out once more, for a rock and roll faculty skit at a department Christmas party, according to Barry Johnston, senior ChemE lecturer at MIT. Bob recalls the performance as "a good chance for students to laugh."

Outside academic departments and beyond national borders, the global energy crisis cast a pall over many Y2K galas. By 2000, world leaders and scientists were hotly debating the gravity of climate change and energy needs. In 1997, the Kyoto Protocol set binding targets for reducing greenhouse gas emissions, to be implemented between 2008 and 2012.

In 2005, as the Protocol went into effect, ChemE professor Bob Brown, then-MIT Provost and now Boston University President, announced the formation of MIT's Energy Research Council (ERC). Bob and Ernest Moniz, former undersecretary for the U.S. Department of Energy and an MIT professor of physics, co-directed the ERC. They were charged with crafting MIT's overall energy initiative and coming up with a structure to sustain it.

Bob took up that challenge as he has so many others — methodically and thoroughly — while pursuing his teaching, advising, and research. Whether approaching a research problem or roughing it in the rain, he sticks with the "hallmarks of a careful theoretician. Establish the basic principles, clearly explain your methods, then make systematic advances towards your goal," says Bob's former student, Gareth McKinley (MIT Ph.D. 2007). "Old school, some would call it."

Ever enthusiastic about research and innovation in ChemE and energy studies, Bob acknowledges he does rely on one old-school technology—the blackboard. "Once I worked all night to prepare PowerPoint slides, only to forget to bring them to class. The students were so relieved I used the blackboard! PowerPoints can move too fast for real learning," he says.

THE BINGHAM MEDALIST

In 2006, Bob's colleagues and peers presented him with the prestigious Bingham Medal. Sponsored by the Society of Rheology, the Bingham Medal recognizes outstanding research contributions to the field.

Bob's published research provides a record of those contributions. He has co-authored more than 70 papers with Brown in a particularly productive collaboration.

Bob and Brown also co-advised numerous MIT graduate students. "They formed a unique team," says McKinley. "Working for 'Bob and Bob' was a statement that carried a lot of weight and commitment."

Bob's Bingham lecture, "Rheology and Energy: What Can Rheologists Do?" reflects his growing commitment to bringing his academic research and energy research more closely together.

"The energy business is basically moving fluids around the world. Understanding how they move is crucial. Rheologists work to understand how sea ice breaks up due to climate change and how the stringy slurry from bio-fuel production can be pumped from place to place. The field has plenty of subsurface flow problems to tackle, too," he says, his excitement clear at the prospect of new challenges.

Certainly, Bob's research has contributed to the next generation of leaders in ChemE and related research.

McKinley, now head of MIT's Non-Newtonian Fluid Dynamics Research Group, describes his lab's experimental work on systems ranging from bread dough to spider silk to hagfish slime as "heavily influenced" by Bob and Brown.

Beris of the University of Delaware currently studies modeling and simulations of complex flows, a direct outgrowth of Bob's research on the behavior of complex fluids. And, according to Green, Bob's theoretical work helps provide context and direction for his own research on novel nanomaterials like carbon nanotubes and graphene.

Bob's enthusiasm for passing on his commitment to ChemE education and research is contagious. His eyes light up when he describes his vision for linking students' skills and altruism to grand problems in energy, health, water, and security.

"I'd love to have student groups work on projects like cleaning up Superfund sites or designing concentrated solar power plants," he says, "I'd like to say to them, 'This is one of the world's big problems, and we need your help.' I'd like them to leave MIT with a belief they can solve anything and a sense of responsibility to do so."

Ever enthusiastic about research and innovation in ChemE and energy studies, Bob acknowledges he does rely on one old-school technology—the blackboard.

Between 1998 and 2006, Bob had to believe he could solve anything: He balanced his roles as teacher, advisor, researcher, and department head while traveling almost constantly. In 2004 alone, he traveled to China, Germany, and South Korea to speak on chemical engineering research or education.

Meanwhile, as Bob traveled around the world, oil prices were traveling out of this world. In 2007, the price of crude oil surged over $100 a barrel. Gasoline hovered at $3.00 a gallon—market events unthinkable just a few years before. Carbon footprints, solar panels, bio-fuels, algae-based smog-eaters—a new lexicon of concern about fossil-fuel consumption sprang into popular use.

A different man might have tooted his own horn to say he'd told them so. But that's not Bob. Back in 1999, he and Debbie got rid of one of two family cars to conserve another scarce resource—time. Then, as now, Bob's busy schedule left too few moments to indulge his love for books.

Since then, Bob has taken public transportation—a bus, then a train—so he can read and work during his commute. When he flies, he's always got a book. He enjoys mysteries that feature science or scientists; he prefers authors Clive Cussler, Dan Brown, John Grisham, and Michael Connelly. Bob also enjoys the occasional nonfiction work, such as Jared Diamond's *Guns, Germs, and Steel*.

Bob's wide reading and boundless curiosity add spice to his lectures, keeping students interested, he says.

"My advice to a new teacher is: Connect the material you're covering to current global problems. Invite your students to get involved in thinking about the world's future.

"Another strategy is to bring in history. Students enjoy my illustrating non-Newtonian fluids by referring to the ancient Romans' siphoning bitumen. They like learning that the Deborah Number got its name from the Biblical Book of Judges," Bob says. "It opens their eyes."

ENERGY STUDIES, ChemE AWARDS

The MIT Energy Initiative (MITEI) was established in 2006. Bob and Moniz serve as deputy director and director, respectively; they coordinate MIT's existing energy activities and guide the development of relationships with other institutions, industry, and government agencies.

In 2008, Bob was elected to the National Academy of Engineering, a measure of his scholarship and leadership in academia, according to Bird. The NAE praised Bob for his "outstanding research on non-Newtonian fluid mechanics, co-authoring landmark textbooks, and providing leadership in chemical engineering education."

That year, he presented the Barnett F. Dodge Distinguished Lecture at Yale, on "The Energy/Environment Challenge and MITEI," and the L.T. Fan Distinguished Lecture at Kansas State, on "The Global Energy Challenge: Opportunities for Chemical Engineering Research and Education."

Bob's current projects often combine ChemE and energy research. He and McKinley are working with Chevron on deposition of waxy crude oils on surfaces of pipes in deepwater drilling operations, for example.

Since assuming the deputy directorship of MITEI, Bob has lectured widely on energy and chemical engineering education. He devoted a sabbatical year to establishing MITEI, traveling to Saudi Arabia, Italy, Spain, China, and Singapore on the Initiative's behalf.

In spring 2010, Bob returned to the MIT classroom to co-teach a graduate class, Macromolecular Hyrodynamics, with McKinley and to develop a new ChemE senior design module on concentrated solar power.

Looking ahead, he's quick to cite great examples of how innovative approaches to ChemE education, supported by MIT's Energy Initiative, can prepare students for their futures in the field.

The 2007 MIT Coal Study is one such innovation, he says.

"The Coal Study compared different strategies for carbon capture and sequestration (CCS). ChemE senior design students did all the economic evaluations of capture technologies. They had to see energy issues from new perspectives, and the result was a rigorous and consistent economic analysis of one of the world's biggest problems … and a sense of the relevance of their education.

"MIT and MITEI are bringing together faculty and students from every discipline to focus on energy. We're getting out of disciplinary silos and traditional textbooks. There are no 'solve the problems in chapter 10' in the real world. We're facing complex and urgent global problems," he says. The MIT Energy Studies Minor is a great example of this new interdisciplinary approach.

Ever the ChemE educator, Bob believes ChemE students need a balance of academic and international experience to take on those global problems. Some MIT ChemE students, for example, work at Novartis in Switzerland, at BP in Britain, or at a sugar refinery in India to enhance their abilities to solve pressing world problems.

"U.S. solutions don't always apply in other cultures, including the developing world. Even if graduates work in a big international energy company, they will need to adapt to local cultures," he says.

Whether in a classroom, a lab, or an unfamiliar culture, he wants chemical engineers to be ready to ask themselves 'What kinds of new solutions can we synthesize to solve society's big challenges?' "

Those who know him have no doubt that Bob's impact on the energy world will be at least as great as his impacts have been in the fields of rheology and education. ❒

A LABORATORY EXPERIMENT ON HOW TO CREATE DIMENSIONLESS CORRELATIONS

ROBERT V. EDWARDS[1]
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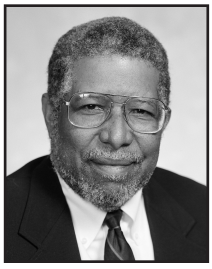
Dimensionless correlations are a prominent feature in the practice of chemical engineering. It is difficult, however, to create a student experiment that will illustrate how they are created. For instance, a pipe flow experiment can be set up where pressure drop is measured as a function of the flow rate. The results can be consistent with the published dimensionless correlation, but the results cannot be called a verification of the correlation unless all the relevant parameters have been varied.

This paper discusses a laboratory experiment in our junior-year laboratory that shows how dimensionless correlations should be constructed. Balls of various densities and diameters are dropped from various heights into a pool of water, and the maximum depth reached by the ball is recorded for each drop. The variables are the liquid density, the ball density, the ball diameter, the initial height above the liquid, and finally, the greatest depth of penetration. The experimental apparatus is shown in Figure 1.

For many years, this experiment was a great frustration to the students. They kept futilely attempting to use the Buckingham Pi Theorem to find the appropriate dimensionless groups. In fact, the Buckingham Pi Theorem is an existence theorem. It tells us that given m quantities describing a physical situation and n fundamental units (mass, length, etc.), a dimensionless description of the situation can be written as a function of m-n dimensionless groups. The proof is a construction proof wherein an algorithm is constructed to compute example m-n dimensionless groups. Students are sometimes aware that the version of the theorem found in chemical engineering texts also states that the product of any dimensionless group to any power times any other dimensionless group to any power is also a legitimate dimensionless group. What they don't always understand is that the latter creates an infinite combinatorial problem. The appropriate groups can be obtained only by a low-probability accident. The latter method will fail in situations like time-dependent heat transfer problems where the theorem predicts too many dimensionless parameters. There are more elaborate versions of the theorem in the literature that claim to guide the user in which variables and parameters can be combined, but they contain no physics and are thereby suspect as a guide to constructing a physical theory.



Robert V. Edwards *was a professor of chemical engineering at Case Western Reserve University in Cleveland, OH. He carried out his undergraduate and graduate education at Johns Hopkins University, and received his doctoral degree in 1968. His research interests included dynamic laser light scattering, stochastic modeling, statistical data processing, and turbulence measurement techniques. He was a fellow of the AIChE. Prof. Edwards passed away in December 2008.*

1 Prof. Robert Edwards passed away after submitting this paper. Final revisions to the paper were made by Prof. Daniel Lacks, Department of Chemical Engineering, Case Western Reserve, daniel.lacks@case.edu. Correspondence regarding this paper can be directed to Prof. Lacks.

THEORY

The appropriate method is the one suggested decades ago by Bird, Stewart, and Lightfoot,[1] and reinforced by Sides.[2] Basically it says that the physics that control the process must be known in order to find the appropriate dimensionless groups. The method consists of writing down the governing differential equation and then making that equation dimensionless using the boundary and initial conditions. The functional forms of the governing dimensionless groups will reveal themselves after some manipulation. Importantly, this procedure is valid for approximate models where only the dominant variables are treated.

The core of this problem consists of determining the velocity of the ball in the water as a function of the ball's physical parameters, the parameters of the water, and time. When the velocity goes to zero, the ball is as deep as it is going to get (recall, the balls have a specific gravity less than 1, so they ultimately float).

It is easy to estimate the initial ball velocity in the water, v_o, when dropped from a height L, by assuming that the initial potential energy is completely converted to kinetic energy.

$$v_o = \sqrt{2gL} \tag{1}$$

where g is the gravitational acceleration. This assumes that that velocity is well under the terminal velocity and the effect of air friction is negligible. The ball will lose some speed when it penetrates the water surface, but it will be assumed that loss is negligible; recall that the purpose of this analysis is to develop a functional form to be used in a fitting procedure, rather than to solve the full equations rigorously, and as pointed out above, reasonable approximations do not damage our ability to obtain a reasonable correlation. Once in the water, the differential equation that describes the acceleration of the ball is given by Newton's second law,

$$\left(\rho_b \frac{\pi D^3}{6}\right)\frac{dv}{dt} = F_b + F_f \tag{2}$$

where v, D, and ρ_b are the velocity, diameter, and density of the ball. The buoyant force, F_b, according to Archimedes, is simply

$$F_b = \frac{\pi D^3}{6}\left(\rho_b - \rho_w\right)g \tag{3}$$

where ρ_w is the density of water. The friction force is estimated in typical chemical engineering fashion using another dimensionless correlation (see Bird, Stewart, and Lightfoot),

$$F_f = -\frac{1}{2}\rho_w v^2 \frac{\pi D^2}{4} f\left(\mathrm{Re}\right) \tag{4}$$

where the dimensionless friction factor f is a function of the Reynolds number $\mathrm{Re}=\left(\rho_w vD\right)/\mu$, and μ is the fluid viscosity. The Reynolds number is a function of the velocity of the ball, and it changes as the ball moves through the fluid.

The equation of motion can now be written

$$\rho_b \frac{\pi D^3}{6}\frac{dv}{dt} = \frac{\pi D^3}{6}\left(\rho_b - \rho_w\right)g - \frac{1}{8}\rho_w \pi D^2 v^2 f\left(\mathrm{Re}\right) \tag{5}$$

In principle, this equation could be solved numerically, but it is not necessary to do so to get the appropriate dimensionless groups. By dividing Eq. (5), by the parameters on the left-hand side and g, and defining the dimensionless velocity $v^* = v/\sqrt{2gL}$, the result is

$$\sqrt{\frac{2L}{g}}\frac{dv^*}{dt} = \frac{\left(\rho_b - \rho_w\right)}{\rho_b} - \frac{3}{2}\frac{\rho_w}{\rho_b}\frac{L}{D}v^{*2} f\left(\mathrm{Re}_0 v^*\right) \tag{6}$$

where $\mathrm{Re}_0 = \left(\rho_w\sqrt{2gLD}\right)/\mu$ is the initial Reynolds number as the ball enters the fluid. Since all the terms on the right-hand side are already dimensionless, the left-hand side must be as well. By defining dimensionless time as $t^* = t\sqrt{\frac{g}{2L}}$, the equation obtained is

$$\frac{dv^*}{dt^*} = \left(1 - \frac{\rho_w}{\rho_b}\right) - \frac{3}{2}\frac{\rho_w}{\rho_b}\frac{L}{D}v^{*2} f\left(\mathrm{Re}\right) \tag{7}$$

Eq. (7) implies that the solution for the dimensionless velocity will be of the form

$$v^* = v^*\left(t^*; \frac{\rho_w}{\rho_b}, \frac{L}{D}\mathrm{Re}_0\right) \tag{8}$$

which demonstrates the dimensionless groups that affect the trajectory of the ball.

The maximum depth the ball reaches, h, is obtained as

$$h = \int_0^{t_{max}} v\left(t\right)dt \tag{9}$$

where t_{max} is the time at which the ball reaches its maximum depth. Using the definitions for the dimensionless velocity and time, this leads to

$$h = \sqrt{2gL}\sqrt{\frac{2L}{g}}\int_0^{t^*_{max}} v^*\left(t^*\right)dt^* \tag{10}$$

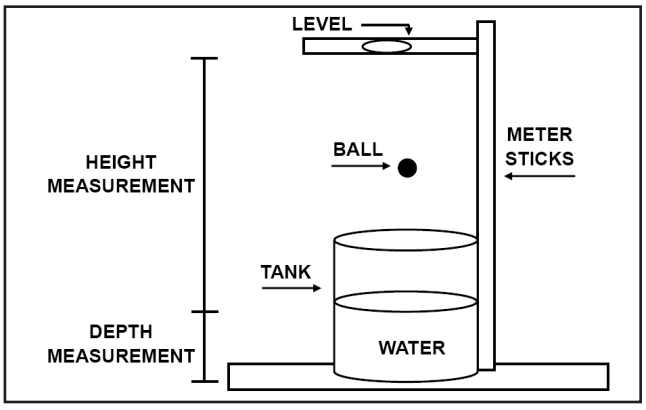


Figure 1. *Ball-Dropping Apparatus.*

and further simplification leads to

$$\frac{h}{L} = 2\int_0^{t^*_{max}} v^*\left(t^*\right)dt^* \tag{11}$$

Eq. (11) implies that

$$\frac{h}{L} = \frac{h}{L}\left(t^*_{max}; \frac{\rho_b}{\rho_w}, \frac{L}{D}, Re_0\right) \tag{12}$$

Now, the value of t^*_{max} is determined by the condition $v^*(t^*_{max})=0$, which in combination with Eq. (8) implies

$$t^*_{max} = t^*_{max}\left(\frac{\rho_b}{\rho_w}, \frac{L}{D}, Re_0\right) \tag{13}$$

By combining the above two equations, the result is found that

$$\frac{h}{L} = \frac{h}{L}\left(\frac{\rho_b}{\rho_w}, \frac{L}{D}, Re_0\right) \tag{14}$$

which shows how the dimensionless depth to which the ball falls will depend on a set of dimensionless physical parameters.

At this point, the solution is not known, but common engineering practice is to attempt a *correlation* of the form

$$\frac{h}{L} = A\left(\frac{\rho_b}{\rho_w}\right)^a\left(\frac{L}{D}\right)^b\left(Re_0\right)^c \tag{15}$$

where the constants A,a,b,c are the parameters that minimize a least squares sum. There is not enough space here to cover the details, but the fit should never be done by taking the logarithm of the expression above and doing a least squares fit to the linearized expression; the result would be biased coefficients. Modern computer power makes the computation simple using an optimizer like "Solver" in Excel®.

One final question. Having used the computer to estimate the fit parameters, how robust are those estimates? In principle, if the experiment is repeated, different parameters will result. The important question is "How large a variation is expected from experiment to experiment?" The answer to this question also affects the appropriate number of significant figures it makes sense to report. The method used here is the maximum likelihood estimate[3] of the parameter variance for the case where the errors in the depth estimate are Gaussian. Under these circumstances, the variance of the parameters from experiment to experiment is proportional to the average measurement error and inversely proportional to the sharpness of the least squares minimum, taken as the expected second derivative at the minimum. It can be shown that the parameter estimate error can be estimated by the following procedure[3]: First, the Fisher information matrix,

$$F_{pq} = \sum_n \frac{1}{s^2}\left.\frac{\partial y}{\partial \alpha_p}\right|_n \left.\frac{\partial y}{\partial \alpha_q}\right|_n \tag{16}$$

is estimated, where y is the function being fit [Eq. (15)], the α_p are the parameters of the fit [A, a, b, c in Eq. (15),] and the derivatives are evaluated at the set of parameters (Re_0, D, and ρ_B) used for the n^{th} experimental trial. The parameter s^2 is the estimated measurement variance, which is the average square of the deviation of the theory from the measurement estimated after the successful fit. Then, the estimate of the reproducibility variance for each of the parameters is given by

$$\sigma_p^2 = F_{pp}^{-1} \tag{17}$$

where F_{pq}^{-1} is the inverse matrix of F_{pq}. This methodology is described in detail elsewhere.[3] While these calculations look cumbersome, they are easily done using a spreadsheet program like Excel®.

RESULTS AND DISCUSSION

A randomly selected student's set of laboratory data is analyzed as described above. This data included the maximum depths reached by 14 different balls (with various D and ρ_B) dropped into water from 3 separate heights above the water; the parameter ranges were 2.5 cm < D < 6.5 cm, 0.55 g/cm^3 < ρ_B < 0.90 g/cm^3, and 34 cm < L < 141 cm, and the maximum depths that the balls reached were in the range 11 cm < h < 47 cm. This data was fit with Eq. (15), and Figure 2 shows a plot of the measured value of the depth vs. the theoretical depth obtained from the fit above. As is apparent from the graph, the fit is an overall success. To quantify the uncertainties, the Fisher information matrix and its inverse are calculated,

$$F_{pq} = \begin{pmatrix} 704.93 & -331.06 & 2973.0 & 13571 \\ -331.06 & 198.01 & -1437.0 & -6388.8 \\ 2973.0 & -1437.0 & 1311.0 & 57099 \\ 13571 & -6388.8 & 57099 & 262630 \end{pmatrix}$$

$$F_{pq}^{-1} = \begin{pmatrix} 0.3399 & -0.00542 & -0.01138 & -0.01522 \\ -0.00542 & 0.02554 & 0.00194 & 0.00048 \\ -0.01138 & 0.001937 & 0.00194 & 0.00021 \\ -0.01522 & 0.00048 & 0.00021 & 0.00076 \end{pmatrix}$$

to obtain a final result for the fit of the dimensionless correlation to the experimental data,

A= 1.60 ± 0.51

a= 1.32 ± 0.14

b= -0.61 ± 0.04

c= 0.062 ± 0.024

Note that the uncertainty estimates listed are the σ_p, which describe the standard deviations for the uncertainties in the parameters, such that ranges of $\pm 1\sigma_p$ are associated with 68% confidence limits, and $\pm 2\sigma_p$ are associated with 95% confidence limits, etc.

Students often try other functional forms, however, which are not dimensionless, for the fitting. For instance, from this same data set, the student reports that the fit

$$h = 0.3089\text{cm}\left(D^{0.79}\right)\left(\rho_b^{1.06}\right)\left(L^{0.26}\right) \tag{18}$$

is even better than the fit to Eq. (15), in that the R^2 calculated with this fit is larger. Students typically do not know what R^2 is a measure of, much less how large a change is meaningful. That should be pointed out to students, but even more important is that they should recognize that this second fit would tell them nothing about what might happen if the experiment were carried out using a Newtonian oil rather than water. The first correlation should do a good job of predicting the change in behavior since it is dimensionless and contains the essential physics of the problem, including relative densities and the effect of viscosity.

The method demonstrated to derive the appropriate dimensionless groups above is quite robust, but it can give different functional forms. For instance, if the velocity were made dimensionless by embedding it in the Reynolds number, a different form would have been obtained. Following the same methodology as above, the form for the correlation would be

$$\frac{\rho_w^2 hgD^2}{\mu^2} = A'\left(\frac{\rho_b}{\rho_w}\right)^{a'}\left(\frac{\mu^2}{\rho_w^2 gD^3}\right)^{b'}\left(\frac{\rho_w\left[\sqrt{2gL}\right]D}{\mu}\right)^{c'} \tag{19}$$

With no loss of generality, this expression can be multiplied by the second dimensionless group to give

$$\frac{h}{D} = A'\left(\frac{\rho_b}{\rho_w}\right)^{a'}\left(\frac{\mu^2}{\rho_w^2 gD^3}\right)^{b'}\left(\frac{\rho_w\left[\sqrt{2gL}\right]D}{\mu}\right)^{c'} \tag{20}$$

This functional form is legitimate, but not as desirable as Eq. (15) because it stresses the viscosity, which was not varied in the experiment. In contrast, in Eq. (15), the viscosity only appeared in the friction factor correlation where the dependence on the Reynolds number is well tested.

All three versions of the correlation have the same dependence, within experimental error, on the variables used: the ball density, ball diameter, and height of the drop. The dimensionless versions are preferred if only because they give the engineer some guidance as to what experiments need to be done to firm up the correlation and what may happen when liquids other than water are used. More experiments should be done where the surface tension and viscosity are varied.

The example shown here gives an indication what information can be extracted from experimental data. Another instructor has used this same experiment as a vehicle to demonstrate randomness in experiments and examines the sample size dependence for the uncertainty in the estimate of the mean, and whether or not the probable distribution is Gaussian.

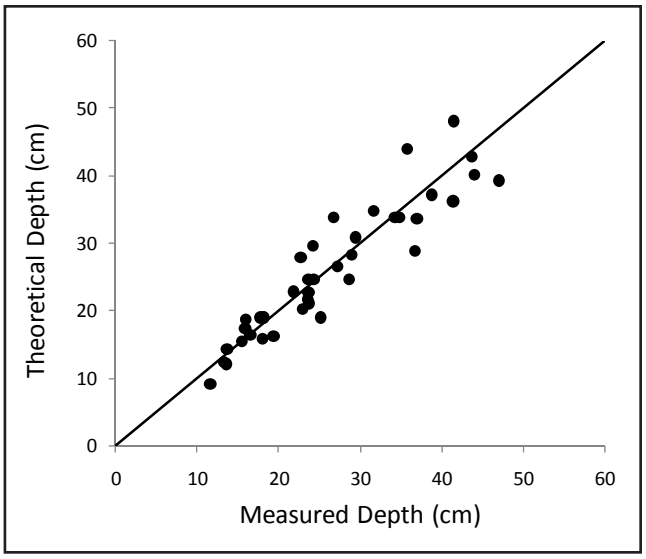


Figure 2. *Relationship between the measured maximum depth of the dropped balls and the fitted (theoretical) values. The line denotes points of equality of the measured and theoretical values.*

NOMENCLATURE

A	proportionality constant in correlation
a, b, c	exponents of dimensionless terms in correlation
D	diameter of ball
f	friction factor for a sphere
F_b	buoyancy force
F_f	frictional force
F_{ij}	ijth element of the Fisher information matrix
g	gravitational acceleration
h	maximum depth reached by ball
L	height ball is released above water
Re	Reynolds number
Re_0	Reynolds number at entrance to fluid
s^2	Estimated measurement variance
t	time
t*	dimensionless time $t\sqrt{g/2L}$
v	velocity of the ball
v*	dimensionless velocity of ball $v/\sqrt{2gL}$

Greek Characters

α_k	kth fitting parameter
ρ_b	density of ball
ρ_w	density of fluid

REFERENCES

1. Bird, R.B., W. Stewart, and E.N. Lightfoot, *Transport Phenomena*, John Wiley and Sons, New York (2002)
2. Sides, P.J., "Scaling of Differential Equations, Analysis of the Fourth Kind," *Chem. Eng. Educ.*, **36**, 232 (2002)
3. Edwards, R.V., *Processing Random Data: Statistics for Engineers and Scientists,* World Scientific Publishing Co., Singapore (2006) ❐

Random Thoughts . . .

THE LINK BETWEEN RESEARCH AND TEACHING

1. Does It Exist?

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For the past half-century, research performance has been the main—and sometimes the only—criterion for tenuring and promoting engineering faculty at research universities, and it's becoming increasingly important at institutions whose primary mission has traditionally been teaching. This trend has had unfortunate consequences. Intense pressures to bring in grants and publish papers force professors to spend most of their time on their research and the minimum they can get away with on their teaching, relationships, and health—and the quality of the latter three often shows it. Faculty members with strong research records and below-average teaching routinely get to be full professors, while outstanding teachers with below-average (and sometimes average) research productivity don't get tenure. Depressingly many research papers are published that have little or no impact on technology or society and are never cited by anyone other than their authors, and core engineering courses stagnate, even though globalization has dramatically changed the skills engineers will need in the coming decades.

If university administrators were being honest, they would state that they need massive amounts of external research funding to function, and while teaching also matters, the main determinant of a faculty member's value to them is scholarly achievement. No administrator would dare say that publicly, though, since to many stakeholders—parents, potential and current students, alumni, donors, and legislatures—education is more important than research. The chancellor of a university that proclaimed teaching to be of secondary importance would have to face some hard and unwelcome questions.

So what happens instead is rationalization. Chancellors, provosts, and deans routinely declare that teaching is their institution's most important function, and to justify the heavy dominance of research in the criteria for faculty hiring, tenure, and promotion, they claim that research and teaching are inextricably linked—so much so that only productive researchers can be good teachers. They offer that proposition as a self-evident truth with (ironically, considering the subject) no supporting evidence whatever.

There is no logical reason to expect productivity in research and effectiveness in teaching to be closely related, since research and teaching have different goals and require different skills and personal attributes. The goal of research is to advance knowledge, while that of teaching is to develop and enhance abilities. Excellent researchers must be observant, objective, skilled at drawing inferences, and tolerant of ambiguity; excellent teachers must be skilled at communication, familiar with the conditions that promote learning and expert at establishing them, approachable, and empathetic. Having both sets of traits is clearly desirable but not at all necessary to succeed in one domain or the other. Moreover, first-class teaching and first-class research can each consume well over 40 hours a week, so that time spent on one activity is inevitably time taken from the other. It should therefore come as no surprise if studies reveal no significant correlations between research productivity and teaching effectiveness.

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As it happens, many studies have been performed and that's exactly what they reveal. Most arguments for requiring all faculty members to be active researchers relate to how research *can* enhance teaching, but a recent review of the literature[1] demonstrates that the potential enhancements are not generally found in practice. The next few paragraphs list the most common arguments and summarize what the studies show about them. For details and citations, see Reference 1.

* * *

Argument: *Research productivity correlates positively with teaching effectiveness*.

Fact: Wrong. Correlations between numbers of papers and grants and measures of teaching quality such as student evaluations, peer evaluations, and learning outcomes are mostly negligible and sometimes negative.

Argument: *Research-intensive universities provide the best undergraduate education*.

Fact: Wrong. In reality, significant negative correlations have been found between a university's research orientation and numerous student learning and satisfaction outcomes.

Argument: *Only active researchers are sufficiently current in science and engineering to be viable teachers*.

Fact: Never demonstrated, and almost certainly wrong for all but advanced graduate courses on the instructors' research specialties. In recent decades applications of most core undergraduate and graduate courses have expanded and impressive resources for teaching those courses have become available, but basic course content has not changed by all that much and little research is now done on that content. Pedagogical experts are much more likely than disciplinary researchers to know how to modernize most core courses appropriately.

Argument: *Faculty with active research programs bring their research into the classroom and use it to inform and enliven their teaching*.

Fact: Usually wrong, especially in undergraduate classes, and when research is integrated into teaching it's not always a good thing. Most current research is well beyond the scope of all but advanced graduate courses, and rigid curricula make it challenging to bring in new material. Some instructors do discuss their research in class and some of their students appreciate their enthusiasm, but other students complain about excessive digressions from basic course content and/or the instructors' apparent lack of interest in teaching that content.

Argument: *Research experiences enhance undergraduate education*.

Fact: True for some students. Participation in undergraduate research correlates significantly with curricular retention of African-American students (but not of other groups), a number of self-reported growth measures and research skills (but not externally measured cognitive skills), and pursuit of graduate study. Even when the argument is supportable, however, it does not justify requiring all faculty members to be active researchers. For one thing, it presumes that active researchers are likely to be better than their more teaching-oriented colleagues at designing and supervising undergraduate research. No supporting evidence exists for this presumption; in fact, much undergraduate research directed by research faculty has students functioning more as unpaid lab technicians than as true researchers. Moreover, undergraduate research is resource-intensive, and at most universities relatively few undergraduates engage in it. Incorporating inductive methods such as inquiry-based, problem-based, and project-based learning into core class instruction could produce many of the same benefits as undergraduate research for more students at a lower cost.[1]

* * *

In short, the unwritten rule that all university faculty should be active researchers places unreasonable and unhealthy demands on faculty members (especially untenured ones); weakens departmental teaching programs; keeps potentially outstanding teachers from devoting enough time and energy to teaching to realize their potential; deprives students of some inspirational and possibly life-changing instructors, mentors, and role models; and is unsupportable by either logic or research.

Which leaves us with two questions. (1) If most of the potential synergies between research and teaching are not being achieved in practice, what can be done to better achieve them? (2) How can schools and departments recognize, reward, tenure, and promote outstanding teachers with little interest in traditional research without compromising their institution's research mission or cash flow? Answers will be suggested in the next column.

REFERENCE

1. Prince, M.J., R.M. Felder, and R. Brent, "Does Faculty Research Improve Undergraduate Teaching? An Analysis of Existing and Potential Synergies," *J. of Eng. Educ.*, **96**(4), 283 (2007), <http://www.ncsu.edu/felder-public/Papers/Teaching-Research(JEE).pdf> ❐

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

THE SOCCER BALL MODEL:
A Useful Visualization Protocol for Scaling Concepts in Continua

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The major characteristic that sets an engineer apart from every other profession in the world is his/her ability to apply the concepts of scaling/up-scaling to a variety of situations. What do we mean by scaling? Well, take for instance a chemist working in the laboratory designing a new drug for a company. Would this chemist be your first choice to take that laboratory synthesis and convert it to a process that produces thousands of tons of that drug per year? Probably not; however, a chemical engineer would be an excellent candidate. Similarly, if building an airplane, scientists (physicists, material, computational) would not be the first choices that come to mind, in spite of the obvious useful roles of their professions. An aeronautical engineer would most likely be the selection that makes everybody comfortable. The same can be said for building structures (bridges, buildings, etc.) where civil engineers are the masters, and for the scaling of industry where industrial/managerial engineers are very skillful. The list is long, but these few examples illustrate the basic concept: Engineers are masters of scaling/up-scaling. Therefore, it is imperative when training engineering students, that they fully grasp the concept of scaling/up-scaling to be able to implement it for practical applications, such as the ones mentioned above.

One important class of up-scaling in engineering education is the different scales involved in describing quantities related to the physics of transport (mass, momentum, energy). In many high school or college-level courses, students are introduced to velocity, density, energy, etc., from a discrete scale point of view.[1] In many engineering applications, however, when studying the physics of transport, it is necessary to develop conservation equations for system properties,

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such as total mass, energy, and momentum for a continuum, or microscopic scale.[2] To accomplish this, the concept of a continuum scale must be introduced to students. Since most students have only been exposed to the physical and chemical concepts related to total mass, energy, and momentum, from a discrete scale point of view, the concept of a continuum scale can be very challenging.

In making the transition from a discrete scale to a continuum scale, one very important pedagogical aspect to keep in mind is that students already have substantial knowledge related to calculating the total mass, velocity, and momentum of a single particle (discrete domain). So from the students' learning point of view, how does the instructor use their previous experience and knowledge with the discrete domain to scale it up to the continuum domain?

Most textbooks do not address this issue. In fact, many of them have suppressed or hidden the process associated with the up-scaling[b,3] on the assumption that all steps and concepts are familiar to the learner, when in fact they are not. This can be frustrating to students and does not enable them to fully understand the importance of the idea of a continuum. Moreover, some textbooks[4] have approached the problem from the point of view of the definition of an intensive property, such as density, and from the traditional definition for the discrete case:

$$m_p = \rho_p V_p \tag{1}$$

where m_p is mass of the particle, ρ_p is density of the particle, and V_p is volume of the particle. They have then simply extended this definition to a continuum control volume, $V_{c(t)}$ as follows:

$$m_s \equiv \int_{V_c(t)} \rho dV \tag{2}$$

where m_s is the total mass of the system under study. Based on Eq. (1) and Eq. (2), it seems that as suggested in Figure 1, two domains exist: A non-applicable (for the system description), or "old" domain (discrete domain) and a "new" domain (continuum domain). As Figure 1 shows, the discrete, or "old," domain is valid for very small scale systems (order of molecules), whereas the continuum, or "new," domain adequately describes the mass of the system for domains of a larger or continuum (microscopic) scale. It is interesting to note that the so-called old domain in Figure 1 is at the molecular level and the concepts learned by students during, for example, high school or college physics are not necessarily at this scale. The molecular scale is a discrete domain, however, and this characteristic offers a bridge for student learning that is effectively used in the Soccer Ball Model (SBM) protocol described in this paper.

The pedagogical challenge described in Figure 1 is that the "old" domain is the domain in which the students are most comfortable and more knowledgeable with the concepts. Students, in general, are unfamiliar with the new domain indicated in Figure 1. Many teaching approaches (in the literature) focus on the new domain and mostly forget the level of knowledge that students already have on the old domain. This situation is probably very familiar to most students, unfortunately, as oftentimes when learning new concepts they are told to "forget" everything they already know; this type of learning approach completely nullifies the knowledge that the students have already acquired. Another option that instructors sometimes use is to force students to imagine a new system where the boundary (or boundaries) are no longer well defined. This, then, requires students to apply "old concepts" to the "new (suddenly introduced)" system. These two options illustrate the many disadvantages for the students when they are not engaged in the process

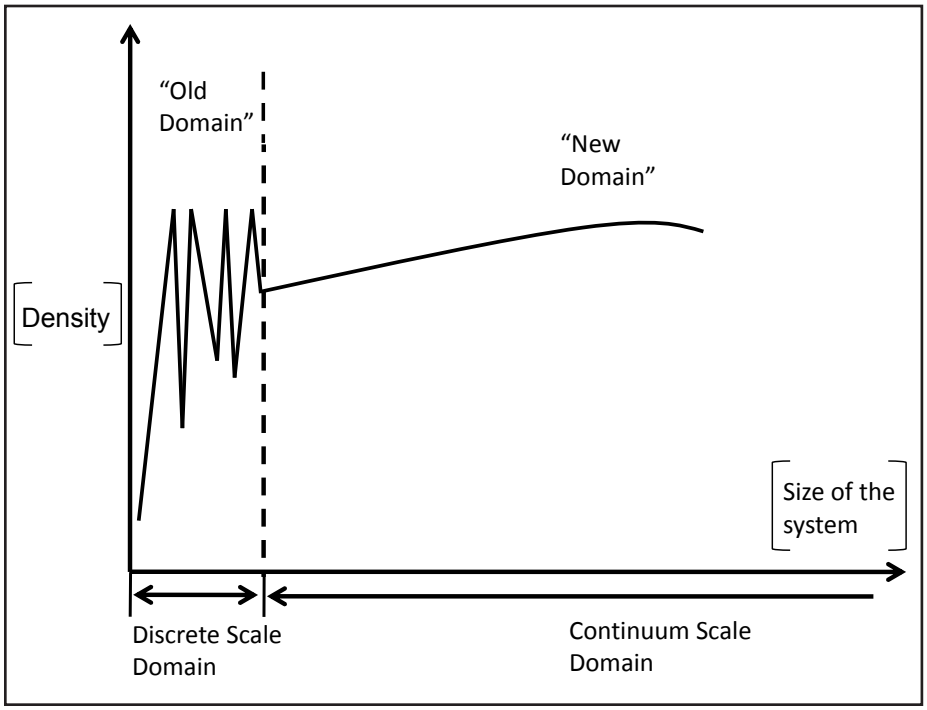

Figure 1. *Sketch of the material density as a function of the size of the system indicating the two scales or domains of interest.*

b The word up-scaling here is used to indicate the change of the description of a property from one scale to another, such as, for example, from the microscopic to the macroscopic scales.

of transforming and adapting what they already know. This suggests the need for adopting a procedure in which students are fully engaged in the process of learning (up-scaling), then coaching them on how to move from one scaling level to the next. Moreover, such a process allows students to build on what they already know about the discrete point of view, and to integrate this knowledge with the new "view" of matter, *i.e.*, the microscopic or continuum scale.

In addition to having an introduction to several scientific concepts from the discrete point of view, students have an adequate background in many complementary subjects including calculus, integral concepts, and algebra. It appears that the instructor could take advantage of this strong scientific and mathematical background to help students in catalyzing the transformation from one scale to the other one in an effective way from the students' learning point of view. In other words, instead of hiding the details about the scaling-up process, by giving the final answer, the instructors could identify one or several activities in which students are exposed to and can learn and reflect on the many aspects involved in the process.[5] In this contribution, we propose a visual[c] process to help with the transformation of scales (domains), *i.e.*, from discrete to continuum, by using soccer balls in conjunction with geometrical domains, mathematical principles, and physical properties. The student is exposed to a very powerful set of pedagogical activities to construct a learning environment that is both practical and effective. An introduction to this environment is given in the next section.

From the learning environment point of view, the SBM protocol is an effective Principal Object of Knowledge, or POK, a tool introduced in the Colloquial Approach[6,7] and later adapted to include other learning environments.[8,9] POKs are tools that allow the facilitator to focus students' learning on a collection of topics or variables conducive to visualizing the process of understanding the different aspects. In this sense, the SBM presents scaling, packing, geometrical, mechanical, and mathematical ideas or concepts in an efficient manner for the process of students' learning.

DESCRIPTION OF THE SYSTEM(S): THE SOCCER BALL MODEL ELEMENTS

Soccer[d] is the world's most popular sport. It is played on the beaches of Brazil, on the grassless surfaces of Argentina, Uruguay, Chile, Africa, as well as on the nap-inviting fields of Europe and North America. Therefore, soccer balls are geometrical objects that are popular among college students in a large number of countries in the world. The International Federation of Association Football, FIFA,[10] (international government of the sport) has five ball sizes shown in Figure 2a. The largest one is number five and it is the official size used in every soccer game at the professional level. The smaller sizes (numbers four, three, two) are used in games depending on player ages, and the smallest ones (number one) are mostly given as souvenirs.

One can observe from Figure 2a that one of the attractive features of the set of soccer balls (decreasing size from the largest one to the smallest one) is the fact that they are all like objects of the same geometry. Although the balls are made of a shell with air at a given pressure, in the soccer ball model it is assumed that they are all made of the same material as the shell (see Figure 3). This assumption usually promotes

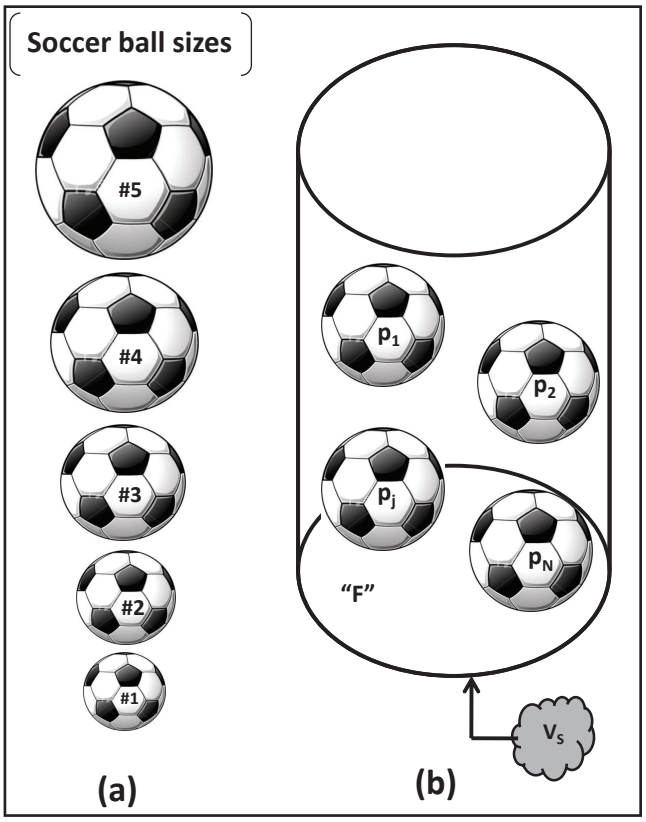

Figure 2. *Elements of the soccer ball model (SBM). (a) Set of the five sizes of soccer balls approved by the FIFA. (b) Container of a given volume,* V_s.

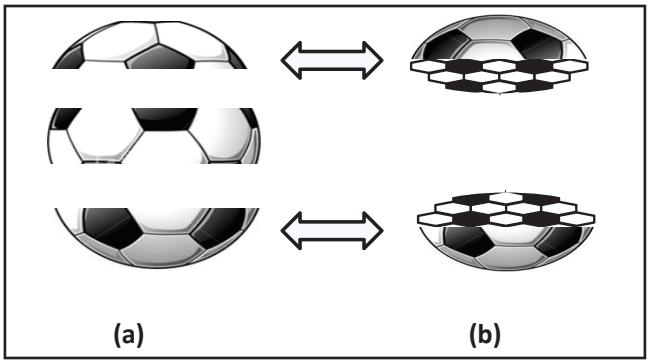

Figure 3*. Visualization of the "soccer ball material."*

c The research on brain-based learning suggests that vision is the most powerful tool for the brain to add new knowledge (Medina, 2008).

d We have used the name mostly used in the United States, however in the rest of the world this foot-based sport is simply called "football."

strong discussions of why this can be proposed and allows the instructor to bring previous vs. new student knowledge to the discussion.

In addition to N balls of a given size, "k" (k=1, 2, 3, 4, 5), the soccer ball model uses a container of a given volume, V_s (t) (see Figure 2b). This container could be either rigid (vessel) or flexible/deformable (bag), and it can be of different geometries, *i.e.*, rectangular, cylindrical, or spherical. For simplicity, a rigid, cylindrical vessel is assumed for the analysis (see Figure 4). The idea of control volume is discussed in connection with the vessel of cylindrical shape. In general, students are introduced to this idea and also to the concept of dimensions associated with the control domains. In fact, they are made aware that these domains could be of one dimension (line), two dimensions (surface), and three dimensions (volume)[e].

Figure 4 shows a typical situation that is helpful for the scaling-up analysis of this contribution. The vessel identified before is partially filled with N soccer balls of a given size. The system (vessel + soccer balls) can be viewed as a composite, or a two-phase system with one phase made completely of the N soccer balls and the other one made of the "fluid" filling the void space between the soccer balls. In many classes students are presented with a transparent vessel containing soccer balls to show the different "phases" and spaces. If the experiment is conducted in a regular classroom, the fluid can be associated with "air"; however, a discussion is conducted for several different possibilities. The fluid phase is denoted by "F" and the mass associated with it by m_F. The mass associated with the N soccer balls inside the vessel is denoted by m_{SB}. Since

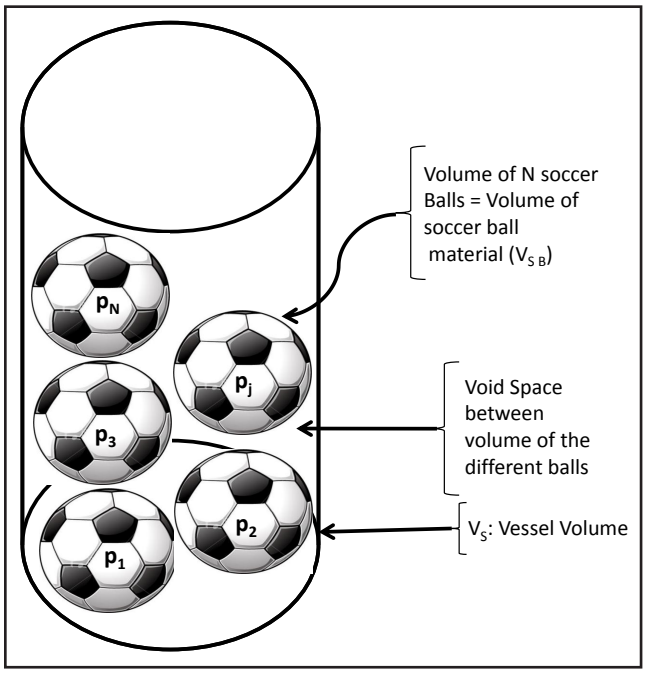

Figure 4. *Sketch of the different components associated with the container identified in Figure 2.*

in engineering many different types of practical systems exist[f], students are introduced to a variety of systems that may have these types of characteristics where the soccer balls can easily be related to "particle models" in a fluid inside a container. One interesting characteristic from the didactic point of view is that these "particles" are discrete objects that the students can see and touch. Once the system in Figure 4 is understood, then a procedure for the mathematical formulation for the total mass of such a system can be developed. The process should start with a system such as the one shown in Figure 4, then steps are made where the students can be coached until the formulation (or scale-up) to a continuum scale can be reached. This is the focus of the next section.

LEARNING PROCESS: TRANSFORMATION OF SCALES

To compute the total mass of the system depicted in Figure 4, let's start by stating some assumptions. We will assume that the volume of the vessel of cylindrical shape is given by V_s. Also, we will assume that a set of "N" soccer balls of the same size, SB_N^k, has a volume, V_{pj} (j=1, 2,...,N), density, ρ_j (j=1, 2,...,N), and mass, m_j (j=1, 2,...,N). Since they are discrete objects, one can easily compute the mass of ball "j" as in the classical college physics textbook[1], *i.e.*:

$$m_j \equiv \rho_j V_{pj},\ j = 1,2,\ldots,N \tag{3}$$

Because of the assumptions stated above, it is immediately recognized that the total mass of the soccer balls can be computed as:

$$m_{SB} = \sum_{j=1}^{N} m_j = \sum_{j=1}^{N} \rho_j V_{pj} \tag{4}$$

and, therefore, the total mass of the system, m_s, with control volume v_s^g can be computed (for the volume of the container) as follows:

$$m_S = m_{SB} + m_F \tag{5}$$

where m_F is the mass of the "F" material. Then in view of Eq. (4), one can express Eq. (5) as:

$$m_S = \sum_{j=1}^{N} \rho_j V_{pj} + m_F \tag{6}$$

Now, one question arises: How can we reduce the mass associated with "F" (m_F) and simultaneously increase the mass

e The idea of domain is connected to the domain concept of a mathematical function, which students are familiar with from calculus courses.

f In general, colloidal and non-colloidal suspensions are very good candidates, but other systems, such as packed or fluidized beds can also be discussed.

g Students are reminded that the N balls must fill up the system completely. The idea of fractions is possible or, alternatively, the choice of V_S is discussed.

of the soccer balls (m_{SB}) while maintaining the volume of the whole system as constant (*i.e.*, V_s=constant)? To answer this question, one should recognize that within the container there are spaces (*i.e.*, void spaces that do not include soccer ball material) and they are filled with a mass of the "F" material (for example, air, see above) that is located between the different balls (see Figure 4). The rest of the spaces within the container are occupied by the soccer balls.

Coaching Point 1: The instructor may want to discuss with the students several examples of particle *packing* systems: marbles of different sizes and sand are excellent examples. The discussion should be focused on the role played by the size of the particles and the void spaces in a given container to help connect the previous knowledge with the analysis of the situation. The instructor should strongly refuse to give answers, and instead act as a facilitator being ready to offer counter examples to the situations brought up by the students. The discussion should lead to the conclusion that *by reducing the particle size, the void spaces are also reduced*. Now as a corollary: What would the effect of this reducing process be on the number of soccer balls? Should N increase or decrease? The hypothesis identified in the exercises/discussions of coaching point 1 may be tested by using the soccer ball model. Here, for example, the number 5 soccer balls should be used as a first step. Those balls, N in total, should be loaded into the container. Both m_{SB} and m_F should be determined or estimated. This is a very useful exercise[h] to acquire a solid idea of the system's characteristics. The instructor could assign vessels of the same volume but of different geometries and ask students if N is the same, or what would change.

Coaching Point 2: The instructor may want to coach the students in calculating the mass of particles in a given volume. The idea of voids and porosity of a packed bed can be easily connected to the problem. Experiments to measure the properties should be discussed. This exercise will produce intense discussions among students regarding very relevant aspects of the different geometries (see coaching point 1, above). Now after the concept identified in coaching point 1 has been understood, students should be able to check it by using the soccer ball model. By using the idea of the size of soccer balls, the process sketched in Figure 5, one should change the number 5 soccer balls to number 4, again measure the mass of soccer ball material and the mass related to the void space, m_F. Once the process or experimental protocol has been identified and tested by students, the next question is at what iteration should it be stopped? The idea of an approximation in engineering becomes useful to address this question. Recall what is intended; to minimize the mass of the void spaces (m_F) up to a point where:

$$m_S \approx m_{SB} \qquad (7)$$

Coaching point 3: The instructor may want to discuss with students at this point the implications or approximations if the protocol were to be implemented in the laboratory. Some of the relevant aspects may include:

1. How do we stop the iteration process to produce the desired approximation in Eq. (7)? *Hint:* The idea of the sequence and the comparison of the mass of the system in iteration k with the k-1 would be helpful:
$$\left\| m_s^k - m_s^{k-1} \right\| < \varepsilon$$
2. The step in the sequence (*i.e.*, "k") may be determined by the accuracy of the instrument being used in the measurements.
3. How valid is the approximation in Eq. (7) for the purposes of reducing m_F and increasing m_{SB}?

By stressing the various geometrical and experimental aspects of the protocol, students gain a very useful hands-on and concrete view of the transformation proposed in the process shown in Figure 5, where the unloading and reloading of the vessel with the different-size soccer balls is sketched. Students soon realize that the set of soccer balls is incomplete for the purposes of perhaps reaching a valid approximation in order for Eq. (7) to hold. This is another great advantage so they can develop possibilities for other systems that will help them to achieve the results. In this sense, the soccer ball model is just

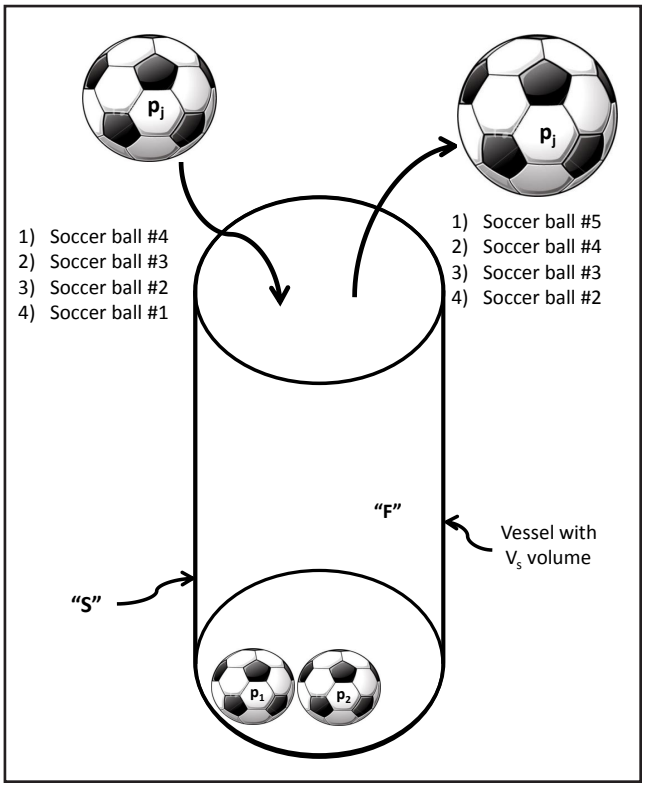

Figure 5. *Sketch of the "Protocol" of reducing the mass of the "F" phase and increasing the mass of "soccer ball material."*

h A very powerful visualization of this protocol can be achieved by using actual soccer balls and containers of different geometries.

a pedagogical promoter, or initiator of a process that allows students to visualize the transformation in the scales.

At the end of the process when the approximation given in Eq. (7) is reached, the mass of the system is given by

$$m_S \approx \sum_{j=1}^{N} \rho_j V_{pj} \tag{8}$$

since m_F is very small it can be neglected compared to m_{SB} for all practical purposes. Now the next question is to check how Eq. (8) can be improved. One excellent possible solution is to continue using small objects (smaller than the smallest soccer ball) as most likely students have proposed, and going to sizes such as, for example, grains of sand and even molecular sizes. Mathematically, this implies

$$m_S = \lim_{\substack{N\to\infty \\ V_{pj}\to 0}} \sum_{j=1}^{N} \rho_j V_{pj} \tag{9}$$

Eq. (9) can be slightly modified to bring it closer to a mathematically useful definition. First we want to map the geometrical situation in the vessel to a mathematical-based domain with incremental volume ΔV_j (see Figure 6). It is useful to discuss with the students the dimensions of the volume of this tiny domain (with respect to the volume of the vessel)[11] with the mathematical concept of incremental volume. From this, now Eq. (9) becomes:

$$m_S = \lim_{\substack{N\to\infty \\ \Delta V_j\to 0}} \sum_{j=1}^{N} \rho_j \Delta V_j \tag{10}$$

Eq. (10) is nothing but a representation of the Riemann sum,[11] that in the limit produces the Riemann integral, *i.e.*,

$$\lim_{\substack{N\to\infty \\ \Delta V_j\to 0}} \sum_{j=1}^{N} \rho_j \Delta V_j \equiv \int_{V_c(t)} \rho dV \tag{11}$$

From Eq. (10) and Eq. (11) now we can write:

$$m_s = \int_{V_c(t)} \rho dV \tag{12}$$

It is very straightforward to conclude that Eq. (12) allows us to compute the total mass of the system from a continuum point of view whose control volume $V_c(t)=V_s$. This equation (valid for a continuum) is derived directly from the discrete objects (*i.e.*, particles=soccer balls) and therefore every physical concept that was valid for a discrete domain is also valid for the continuum domain. By using the visualization protocol as described in this section, we have introduced a different "scale" in the computation of a physical property, *i.e.*, for this case the mass (total) of the system. The total mass of the system (for a single component system, the total mass coincides with the mass of the component) is the primary variable or property that allows us to compute others that are proportional to it (see the section below). Therefore, the transformation from a discrete scale point of view to a continuum scale point of view is relatively straightforward. Students never have to deny that what they learned in the discrete scale is valid for the continuum scale. It is, at the end, a different mathematical description of the same property since the scale has changed.

EXAMPLES AND APPLICATIONS: OTHER VARIABLES OF INTEREST

The learning protocol described in the previous section may be applied to other variables that are relevant for the formulation of conservation principles, such as linear and angular momentum and energy.[12] The steps are identical as for the case of total mass. First, one should start with the mathematical definition of the property for the case of discrete variables and then apply the process identified in the prior

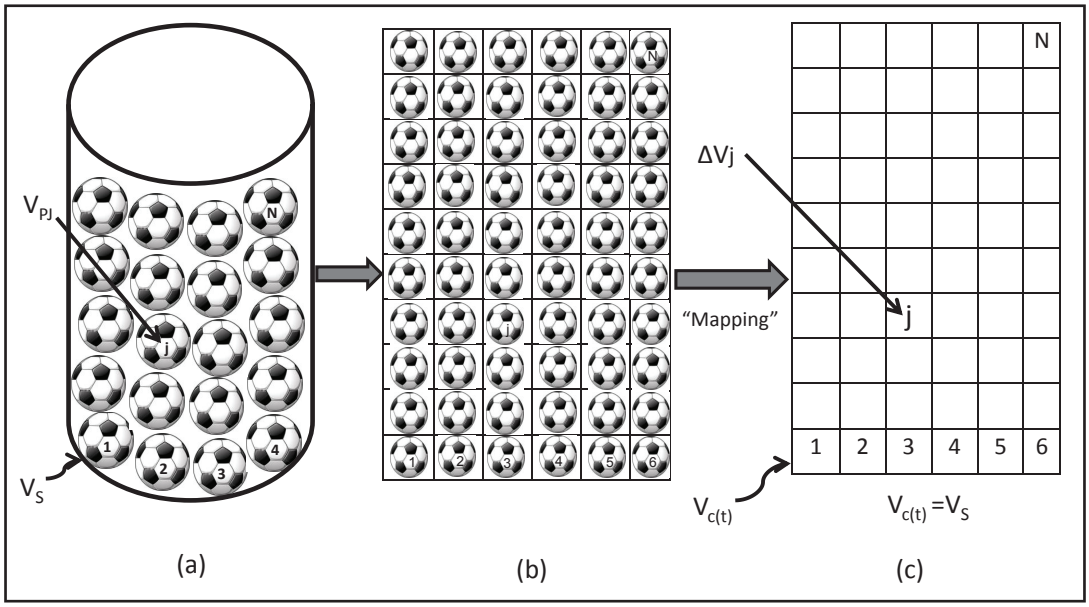

Figure 6. *Mapping of the container volume to a geometrical domain of size V_s. (a): Container filled up with N soccer balls. (b) Side view of the space occupied by the N soccer balls. (c) Geometrical domain showing N incremental volumes of size ΔV_j and with a density ρ_j.*

section to reach the proper mathematical equation for the new property. For example, the linear momentum, $\vec{p}$, for a discrete particle is:

$$\vec{p} = m_p \vec{v}_p \tag{13}$$

for each particle of mass, m_p, and velocity, $\vec{v}_p$. From a continuum point of view, (by using the protocol previously described) we can conclude,

$$\vec{p} = \int_{V_c(t)} \rho \vec{v} dV \tag{14}$$

There is a "shortcut" approach by realizing the mass of the system is given by Eq. (12) and then, by replacing the velocity of the particle by the one of the medium, one arrives to Eq. (14) from the "suggested" form given by Eq. (13). Didactically, this is consistent with the fact that students have a protocol in mind of how the transformation works and is similar to the "mathematical" tricks used frequently in analysis courses to obtain results in a quicker manner. Similarly, energy, E, for the discrete point of view is given by:

$$E = \vec{p} \bullet \vec{v}_p \tag{15}$$

By using the strategy identified above, Eq. (15) is transformed into:[13]

$$E = \int_{V_c(t)} \rho \left[\vec{v} \bullet \vec{v} \right] dV \tag{16}$$

Note: Students may want to use the relation,

$$\vec{p} = \vec{v} \int_{V_c(t)} \rho dV \tag{17}$$

The velocity field $\vec{v} = \vec{v}(\vec{x})$ could, however, be a function of the position inside the control volume, $V_c(t)$, and therefore Eq. (17) will not capture this situation. Eq. (14) and also Eq. (16) will capture non-uniform velocity fields, *i.e.*, Eq. (16) is the most general equation for describing the energy of the system for a continuum scale.

More complicated functions or properties can be expressed from a continuum point of view. For example, the moment around a point, *i.e.*, torque, $\vec{M}$, is given by:

$$\vec{M} = \vec{r}_p \times \vec{F} \tag{18}$$

where $\vec{r}_p$ is the position vector of the force, $\vec{F}$. It is known from mechanics that

$$\frac{d\vec{p}}{dt} = \frac{d}{dt}\left(m_p \vec{v} \right) = \vec{R} \tag{19}$$

From a continuum point of view Eq. (19) can be expressed as,

$$\vec{R} = \frac{d}{dt} \int_{V_c(t)} \rho \vec{v} dV = \tag{20}$$

If $\vec{R}$ is the net force applied to the system, *i.e.*, the one enclosed within the control volume, $V_c(t)$, then from Eq. (18) and Eq. (20):

$$\vec{M} = \frac{d}{dt} \int_{V_c(t)} \rho \vec{r}_p \times \vec{v} dV = \vec{R} \tag{21}$$

in the case that $\vec{r}_p = \vec{r}_p(t)$. Caution must be kept in mind regarding the interpretation of the meaning of the derivative, $\frac{d}{dt}$ in Eq. (19); also, the formulation of Eq. (21) and similar ones requires a careful analysis and discussion that are not part of the scope of this contribution.[12, 14] The protocol of the soccer ball model is actually a helpful tool, from a didactic as well as from the conceptual point of view, since, in practice, all key variables for the description of the conservation principles in a continuum scale can be systematically derived by using such a protocol; or, alternatively, shortcuts based on the protocol are possible.

IMPACT ON STUDENT LEARNING

The SBM protocol was introduced some years ago[7] and it has been systematically implemented in various core courses in fluid mechanics, heat transfer, and transport and reactions, both at the undergraduate and graduate level. The comments by students in course exit interviews have indicated the healthy action of the protocol in helping students build an excellent level of knowledge based on the previous level they bring to the classroom as well as avoid misconceptions. In addition, the protocol has been extremely effective for introducing macroscopic or integral balances from a continuum point of view without much difficulty from the students' point of view. Furthermore, the connection between mathematical concepts learned in calculus and engineering applications, such as the change of scales, is effectively integrated by using elements of the SBM.[3] This, in turn, assists the students in understanding the relevancy of the mathematical tools in engineering applications and enhances the appreciation of their power in, for example, simulating engineering processes.

We believe the protocol of the SBM is an effective tool in removing the students' frustration in understanding a very different description (from the students' point of view) of matter, momentum, energy, and related concepts from a new and more sophisticated scale, *i.e.*, the continuum scale.

SUMMARY AND CONCLUDING REMARKS

This contribution summarizes some of the typical approaches used to introduce students to scaling/up-scaling for variables and properties related to conservation principles in continua. The key aspect is the introduction of a new learning protocol, the soccer ball model, that engages students in every step of the process of transforming scales from a discrete level to build a continuum. The soccer ball model

approach allows students to use what knowledge they have already acquired in previous courses from the discrete point of view, to apply it in a systematic manner, and to obtain the description of properties such as mass, energy, and momentum; these properties are used in conservation equations for the continuum point of view. The protocol identified in the learning environment of the soccer ball model is powerful since students never lose track of the discrete nature of the objects when engaging in building a continuum. They reach this level at the end of the protocol and simultaneously they have been able to develop an excellent idea of the continuum with an equation to compute the given property or properties of the system.

ACKNOWLEDGMENTS

The authors are grateful to students of the transport phenomena sequence (mass, momentum, energy) at the College of Engineering (Florida State and Florida A&M universities), Tennessee Technological University, and Universidad Nacional Mayor de San Marcos (Lima, Peru) for their helpful comments. A presentation with preliminary results was made at the AIChE Annual Meeting (1999) and another one, with additional aspects, as a student poster at the AIChE Annual Meeting, Centennial (2008). We are grateful for the input received. Student (JA) is supported by a diversity fellowsip froom TN Tech. Student (CT) is supported by a fellowship from Chile.

REFERENCES

1. Halliday, D., R. Resnick, and J. Walter, *Fundamentals of Physics*, 7th Ed., New York, J. Wiley (2004)
2. Bird, R.B., W. Stewart, and E.N. Lightfoot, *Transport Phenomena*, New York, John Wiley (2001)
3. Arce, P., M. Oyanader, and S. Whitaker, "The Catalytic Pellet: A Rich Learning Environment for Up-Scaling," *Chem. Eng. Ed.*, **41**(3) 187 (2007)
4. McCabe, W., J. Smith, and P. Harriot, *Unit Operations of Chemical Engineering*, New York, McGraw-Hill (2001)
5. Arce, P., and L. Schreiber, "High Performance Learning Environments," *Chem. Eng. Ed.*, **38**(4) 286 (2004)
6. Arce, P., "Principal Objects of Knowledge (POK's) in Colloquial Approach," Annual Conference *Proceedings* of the American Society for Engineering Education, Section 3413 (2000)
7. Arce, P., "The Colloquial Approach: An Active Learning Technique," *J. of Science Education and Technology*, **3**(3): 145-160 (1994)
8. Arce, P., "How Do We Introduce Continuum Mechanics Concepts to Engineering Undergrads?" (Session: "Undergraduate Forum," Paper 175e, suppl. to *Chem. Eng. Progress* **82** (1999)
9. Arce, P., "Role of Teams in High Performance Learning Environments," Hi-PeLE. Purdue University, School of Engineering Education, West Lafayette, IN, Department Teaching Seminar (2007)
10. Fédération Internationale de Football Association (FIFA). The Official Web site of the Fifa World Cup. <www.fifa.com>.
11. Stewart, J., *Calculus*, Pacific Grove, CA, Brooks/Cole Publishing Company (1999)
12. Whitaker, S., *Introduction to Fluid Mechanics*, Malabar, FL, Krieger Publishing Co. (1981)
13. Bird, R.B., "The Equations of Change and Macroscopic Mass, Momentum, and Energy Balances," *Chem. Eng. Science*, **6**(3) 123 (1957)
14. Whitaker, S., "Newton, Euler, and the Speed of Light," *Chem. Eng. Ed.*, **43**(2), 96 (2009) ❐

Making a CHEMICAL PROCESS CONTROL COURSE an Inductive and Deductive Learning Experience

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Process control has often stood out in the chemical engineering curriculum as a necessary topic that is oddly disconnected from the rest of the curriculum. While control modeling still relies on conservation laws and other fundamentals of chemical engineering, its mathematical focus on process descriptions in the Laplace domain has made it appear to students as a course distinct from "regular" chemical engineering. In reality, process control is key to industrial practice and will draw upon an engineer's theoretical knowledge and practical experience to be effective.

One goal of the addition of inductive and deductive laboratory exercises to this course has been to improve the students' understanding of the linkage between the course and engineering practice. Additionally, the changes are driven by more effective methods of instruction—inductive learning and experiential learning. This approach assumes that physical laboratories are preferred to virtual labs or simulations whenever possible, although virtual labs and simulations can effectively be used to meet objectives for this course.

This paper expands upon the initial experience with incorporating inductive laboratory experiences previously reported.[1]

EXPERIENTIAL AND INDUCTIVE LEARNING

Experiential learning is one approach to engaging students actively in the learning process. Farrell and Hesketh[2] suggest that students typically recall only a low percentage of what they hear, while if they hear and see something done, they may recall closer to half of the experience. If they actually do something, such as conduct an experiment, they are likely to recall significantly more. This is one active-learning approach recognized as contributing to common student learning styles in engineering.[3]

There are numerous examples of incorporation of experiential learning in process control courses.[4-9] Most involve development of experiments, typically required as a part of a distinct one-hour laboratory section extending the course length from three to four semester hours. Clough[10] incorporated experiments directly into the lecture course prior to the addition of the one-hour laboratory section.[11] Others have attempted to add this active-learning component through use of Web-accessible experiments.[12] More recent efforts to include experimentation in process control courses include development of kits using LEGO® RCX® brick and quick-disconnect piping to build desktop process control equipment for in-class use.[13]

Inductive learning refers to the organizational approach by which specific observations are used to lead the learner to more general conclusions. This is effectively the inverse approach of deductive learning, where general principles are used to deduce consequences for specific applications. Most teaching is performed in the deductive mode, but most discoveries, or things learned for the first time, are made inductively. This suggests that induction is a more natural

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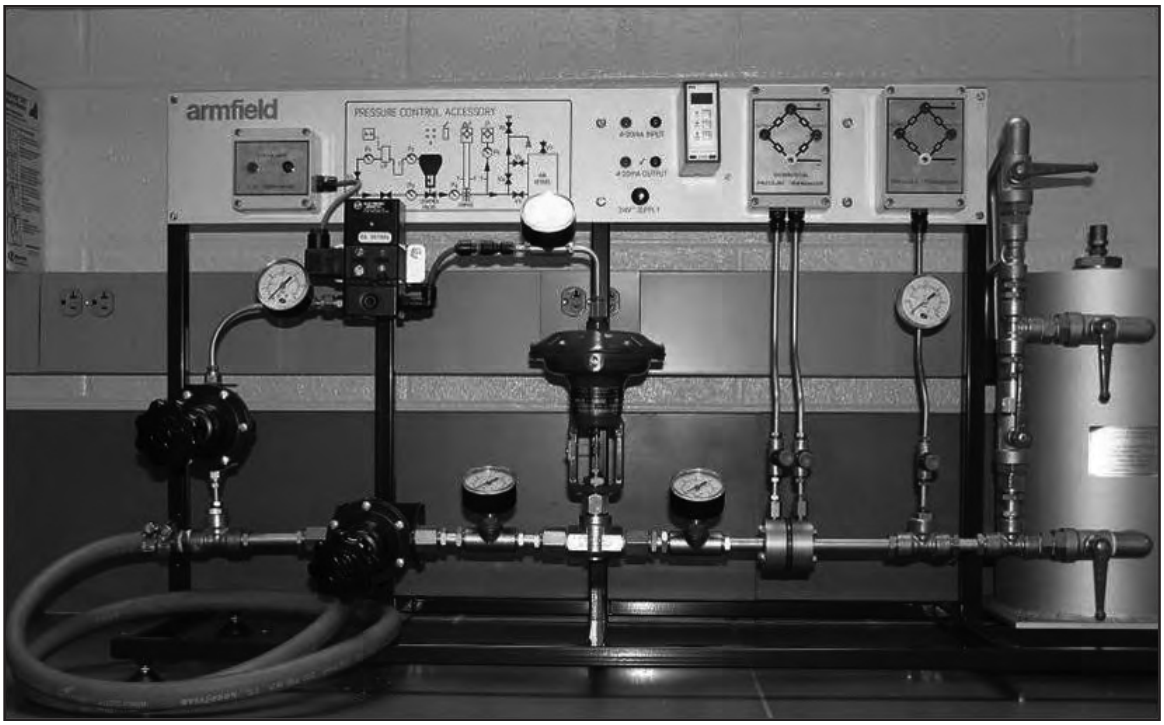
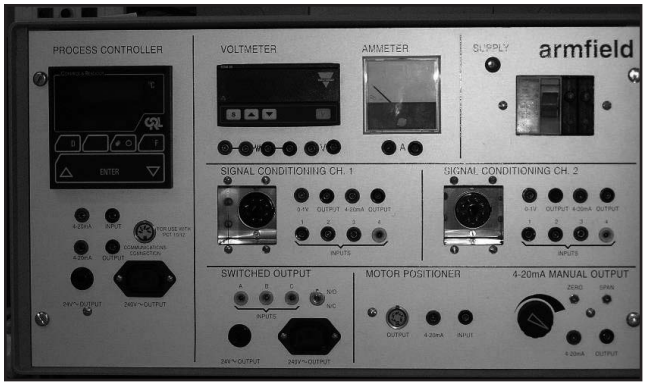


Figure 1. (right) *Pressure regulation apparatus.*

Figure 2. (below) *Control panel for pressure regulation apparatus.*



learning style and more effective for many student learners.[2] Studies on the implementation of different inductive teaching methods in science and engineering have shown that students' conceptual understanding and attitudes toward learning significantly improve, while their performance on tests is better or comparable to traditional teaching methods.[14]

Moor and Piergiovanni[12] describe their application of classroom kits for inductive experiments in a process control course. An inductively structured course in Heat and Mass Transfer is described by Farrell and Hesketh.[1] Hesketh, Farrell, and Slater[15] describe the role of experiential learning when using an inductive style of teaching.

COURSE DESCRIPTION

The course described here is a three-hour lecture course offered during the Spring of the senior year. There is no formal prerequisite other than "consent of instructor," although it draws heavily upon a course in modeling offered during the Spring of the junior year. The expected outcomes for the course are that students should be able to:

- *Apply knowledge of mathematics and science to process dynamics and control*
- *Analyze and interpret different control systems' transient and frequency response data*
- *Design simple control systems for distillation columns and chemical reactors*
- *Identify, formulate, and solve linear control problems*
- *Use engineering tools to analyze control systems*

When preparing to modify the course to add experiments and increase inductive content, the following topics were selected for emphasis:

- *Instrumentation*
- *Relationship of first- and second-order model parameters to responses of real systems*
- *Empirical modeling*
- *Signal conditioning and interpretation*
- *PID controllers and tuning*
- *MIMO interaction*

To modify the course and still conform to reasonable student expectations of time formally committed to the course, lecture time was reduced 10 minutes for every 30 minutes of expected laboratory time. Labs were scheduled at least one to two weeks in advance, with the exception of the first laboratory. Credit for the lab work was given as part of the student homework

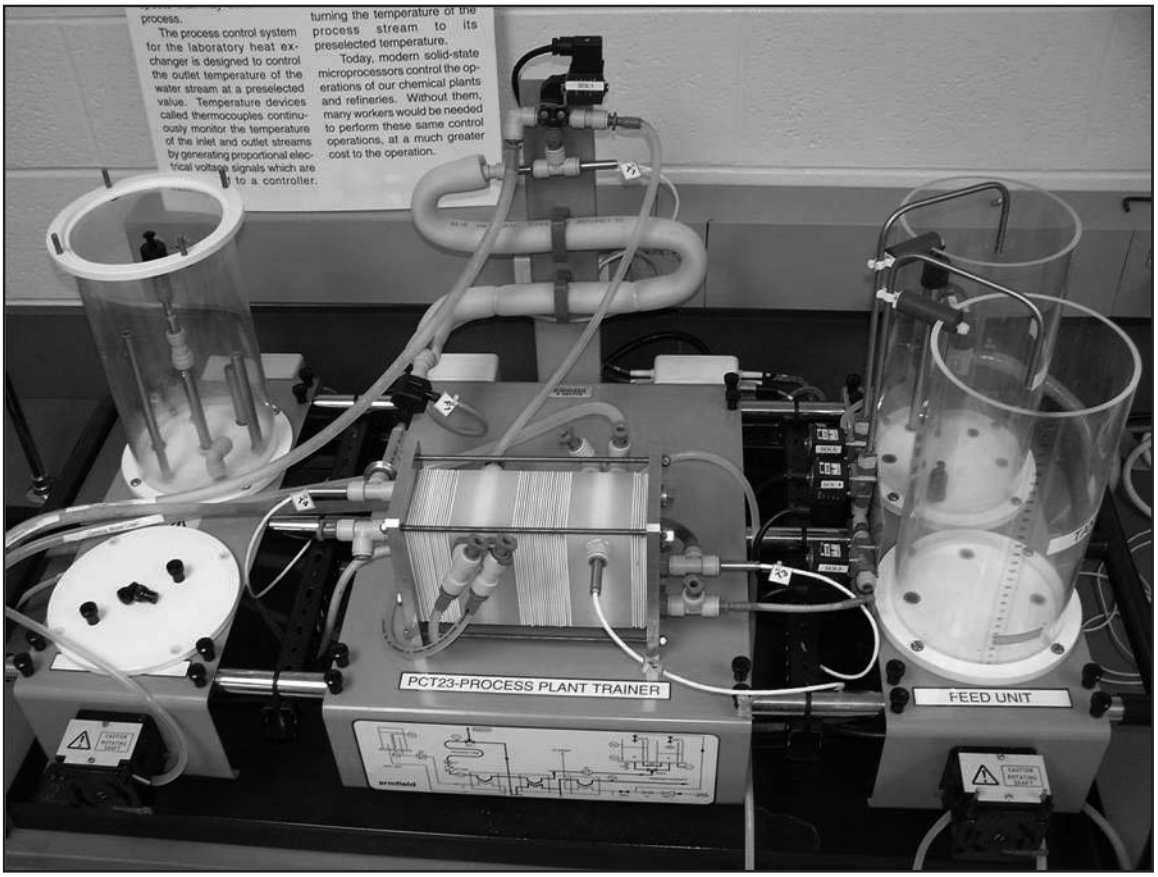


Figure 3. (left) *Process Plant Trainer.*

Figure 4. (below) *Control panel and interface board for the plant trainer.*

grade, which was increased to account for 25% of the total grade for the course. The lab reports were kept simple (mostly fill-in-the-blank and short-answer questions), and the number of textbook-type problems assigned was reduced.

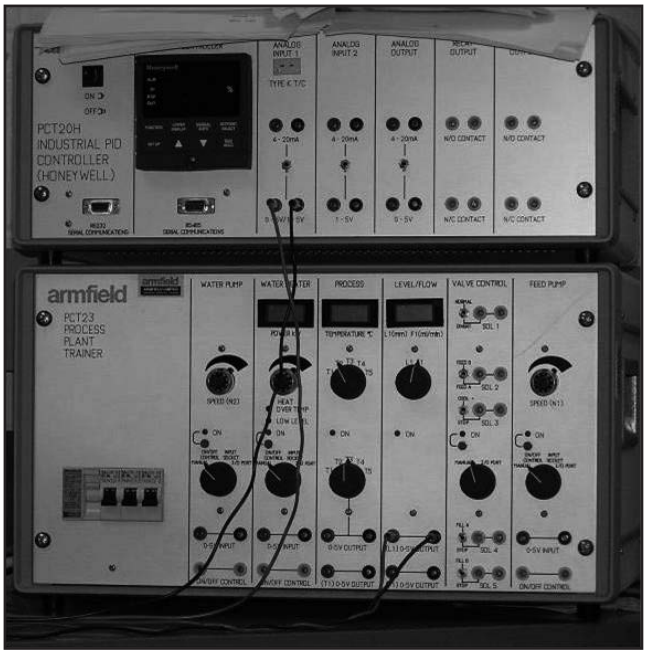
Three class sections at the University of Kentucky have engaged in this modified course to date. The first cohort consisted of 10 students, the second class two students, and the third three students. The quantitative assessment described later in this paper is based primarily upon the first cohort.

THE EQUIPMENT

The commercially available equipment described herein is typical of many devices offered by a number of vendors, including Creative Engineering,[16] Armfield Limited,[17] and Feedback Instruments Limited.[18]

Two devices were used over the course of the semester. The first is a pressure-regulation apparatus (Figure 1) consisting of a pneumatic control valve, various pressure gauges, an orifice meter, a square-root extractor, I/P transducers, and a storage tank. The apparatus can be connected to a control panel (Figure 2) that incorporates an ammeter, a voltmeter, signal conditioner ports, and an industrial-type digital PID controller.

The second device is a "Process Plant Trainer" (Figure 3), which combines three plate heat exchangers, two feed tanks,



a dead-time segment of tubing, various solenoid valves, level sensors, flow sensors, and thermocouples enabling simulation of a variety of fictional processes and control scenarios. This device can be connected to a control panel with an interface board (Figure 4). For some experiments, the apparatus is con-

nected to a PC with MS-DOS-based acquisition and control software. A PLC is also available for use with the system (Figure 5).

THE EXPERIMENTS

The first experiment was conducted the first day of class. Students were presented a syllabus and a homework assignment (including the laboratory assignment), and told to leave their books in the classroom (which was then locked) and come down to the controls lab. Students were briefed on safety rules for the lab, had the exercise explained to them, and then proceeded to complete the first assignment. The objectives for this 30-minute assignment were to:

- *Induce a conceptual understanding of process time constant and gain*
- *Establish justification for automatic control*
- *Demonstrate intuitive use of proportional control*
- *Sketch process behavior*
- *Introduce elements of instrumentation*

Not all objectives were immediately met by the laboratory exercise, but the student experience was used in subsequent lectures to form a foundation for discussion. For example, students were asked to maintain a particular pressure in a (leaking) tank by adjusting the current signal sent to the I/P transducer connected to the pneumatic control valve. We discussed immediately after the lab what everyone did to set the pressure in the tank—starting with big changes when the tank pressure was far from the desired pressure and making smaller adjustments when the error was smaller. Proportional control was introduced a month later referring to this initial experience. Students were able to describe the meaning of a time constant, noting how quickly the pressure apparatus responded (small time constant) compared to a level control response in the process plant trainer (larger time constant). We later modeled both processes and determined the relative magnitude of the time constants, confirming their observations. Figures 6a and 6b are the assignment sheet provided to students. Note that the deliverables were kept simple so that students could focus on observation and not on recording data. This also helped maintain class morale, as students were leery of the added workload of labs in a traditionally lecture-based course.

This exercise was clearly inductive, since students had no background in control prior to the lab. After completing the experiments, we returned to the classroom and discussed what we observed. The benefits were immediately evident in the following class meeting, since students understood why they were learning control. Student discussion quality in that class

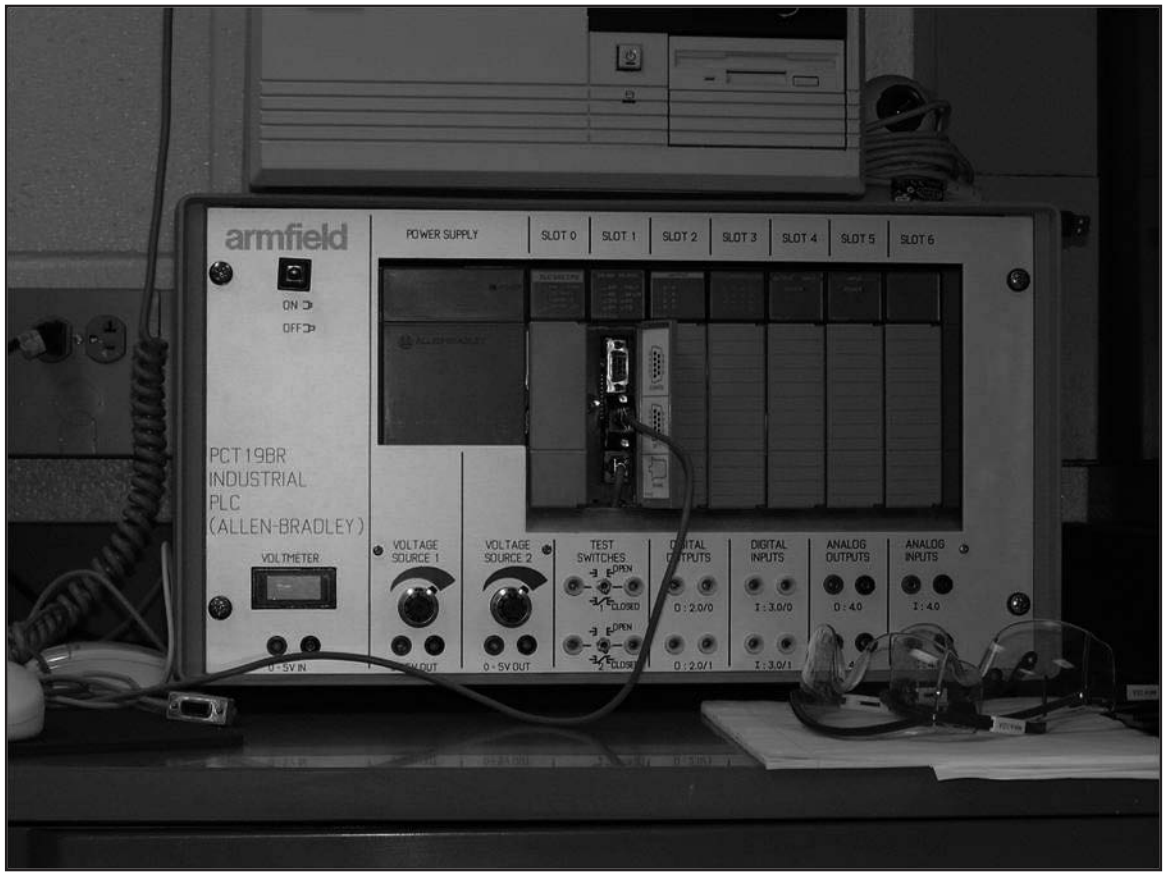


Figure 5. *PLC connected to the plant trainer.*

CME 462

Process Control

Spring 2007

Laboratory Exercise 1

Due: Tuesday, January 9, 2007

What's Process Control About?

Neither of these activities require you to set up equipment. Simply follow the instructions and CAREFULLY NOTE EXACTLY WHAT AND HOW YOU DO what you do. Safety glasses must be worn while in the laboratory.

Part I: Operating Under Pressure (pressure apparatus)

Your goal in this experiment is to maintain a constant pressure of 0.5 bar gauge in the tank.

Using the Manual Output knob, adjust the position of the control valve such that the pressure in the tank is maintained at 0.5 bar. Note how far and how fast you turn the valve in response to the pressure you read. Note the reading on the ammeter when you reach steady-state

Instead of 0.5 bar, you decide to keep the tank at 9 psig. Note again how the system behaved in response to your adjustments.

Be prepared to comment on the following: to achieve the desired pressure, did you turn the knob "all the way". Did the pressure exceed the desired pressure? Which gauge did you use?

Part II: Keeping It Level (plant process trainer)

You want to keep the tank at a level of 50 as indicated by the level meter. While the water is flowing, adjust the rate of rotation of the peristaltic pump to achieve this goal.

Part III: Stuff you have to submit

1. For the pressure apparatus, sketch (qualitative) desired P_{tank}, actual P_{tank}, ammeter reading, and knob position as a function of time over the course of the entire experiment. Include a legend to distinguish between traces.

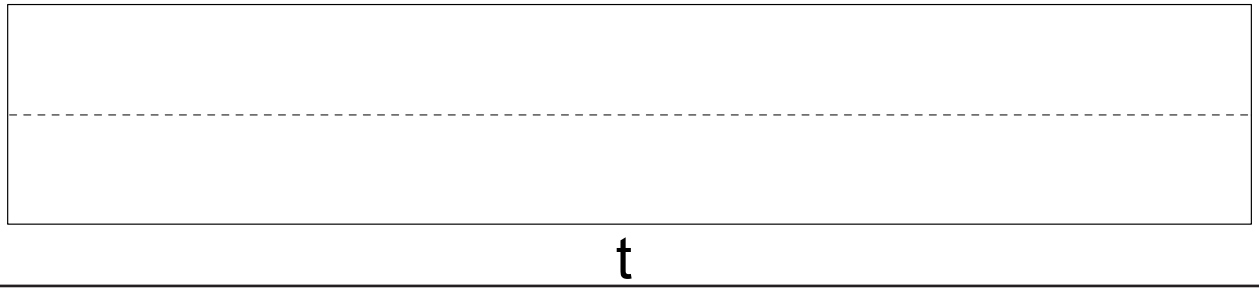
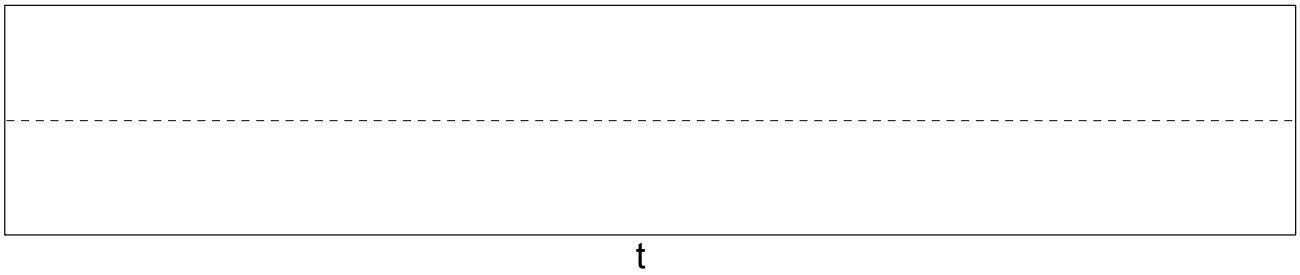


Figure 6a. *Page one of lab exercise conducted during first class meeting.*

2. For the level apparatus, sketch desired level, actual level, and relative pump rotation on the same plot. Include a legend to distinguish between traces.



3. Draw process schematics of both pieces of equipment. For multiple lines going to the same place, draw a single line. Do not include equipment not in use. A process schematic uses pictures and lines to represent equipment and connectivity. See Figures 1.1 and 1.2 in your text.

4. Draw a control schematic of each system. A control schematic contains equipment representations along with indication of what is being measured and what is being manipulated. See Figures 1.4 and 1.5 in your text.

5. What was the key difference (in context of control) between the pressure and level systems?

Figure 6b. *Page two of the initial exercise.*

was far better than in previous offerings, since there was a common experience to form a basis for that discussion. The specific observations made in the lab were later developed into more general principles of process control.

The second laboratory exercise was designed to reinforce the students' understanding of dynamic modeling. Students collected data for a two-tank gravity drainage system, with both tanks connected at their bases. Students then prepared an analytical model of the system, and compared their results with the data they collected. It was a profitable exercise, as some students claimed it was the first time they had theory match experimental data in their chemical engineering laboratory experience. Since students had prior experience in writing balances and designing experiments, this exercise was designed deductively, but still engaged students actively in the process of convincing them of the validity of theory discussed in class.

The third exercise in process identification was designed deductively as well, since students had previously performed regressions of experimental data. Students collected step response data of a multi-step heat exchange process controlled by changes in three process variables. After the lab, they selected an appropriate model and determined model parameters. While it was not part of the official assignment, the highlight of the exercise was the opportunity to wire a controller to a feed valve to eliminate the need to manually maintain an adequate level in a feed tank. Students were provided wiring and a manual, and were told the controller was configured to maintain the level. During the 30 minutes or so required to allow the system to come to steady state, all three groups managed to deduce the appropriate wiring connections to set up automatic feedback control. This experience was also used during lecture when defining terms such as "deadband" and "direct action."

The fourth exercise was the first foray into closed-loop systems. Since closed-loop behavior, PID controllers, controller tuning, and stability had not been discussed in class, this was an inductively designed exercise with detailed instructions on what to do and what to observe. The pressure apparatus was used in conjunction with its orifice meter to maintain a desired flow rate of air. Students used an industrial PID controller and varied the controller gain to make the system marginally stable and unstable. They then observed the difference in response with P and PI control. They rewired the system to bypass the square-root extractor (conditioning the orifice meter signal), observed the difference in system behavior, and were asked to show why it was required.

A fifth exercise concerned a multi-loop system involving both temperature and flow variables. Students were asked to observe which variables interacted, and then to suggest why from general models. They also observed the effect of detuning to account for interaction.

The last exercise required students to run through an exercise in PLC usage involving a ladder program simulating a five-step batch process using the process plant trainer. This exercise was not completed due to communications issues between the PC and PLC.

Time required for each of these exercises varied widely. The first exercise, which involved only flow control, took 30 minutes (for 10 students on two devices) during the first class period. The second and fourth, which also involved flow control, took 30 minutes to an hour, depending on the preparation of the students ("*did you read the instructions?*"). The remaining exercises took about three hours, due to the thermal transfer dependence of the experiments.

ASSESSMENT

After the final exercise, students in the first implementation of this course structure were asked to submit responses to a free-answer survey assessing their perceptions of the labs. Of the 10 students in the sample, nine responded.

1. *Were the laboratory exercises a valuable part of the course?*
2. *Did they help you better understand the course material?*

All nine students indicated that the exercises were valuable and helped in understanding the course material.

3. *Were they more valuable when they served as an introduction to course concepts, or when they reinforced lectures and reading?*

This question was intended to determine whether students preferred the inductively designed labs or deductively designed labs. One-third preferred the inductively designed labs, while the remaining two-thirds preferred the deductive labs. The learning styles of these students were not assessed, so the only conclusion by this instructor is that the students were not considering the learning value of the experience, but were focused on their comfort level during the lab.

This result was confirmed by similar surveys administered to subsequent sections of the course.

4. *Which labs would you recommend be kept? Should any be removed from the course?*

Students expressed a distinct preference for the faster experiments, since much of the time spent on the slower (thermal) labs was spent idly waiting for the system to reach steady state. Later offerings had the apparatus "preheated," but lab times were still longer than students would have preferred.

5. *What changes to the lab/lecture balance would you recommend?*

Students were concerned about the time spent on the thermal labs, and preferred having a regularly scheduled lab section. Due to the number of hours in the current curriculum, this is not an option at this time. This is, however,

the historical evolution of such improvements to a process control course.[9,10]

Other requests included "make the equipment work," referring to problems with a peristaltic pump and with entrapped air in a pressure measurement line.

The labs seemed to improve student performance on exams, but more noticeably students seemed more "tuned-in" during lectures in which the lab results were used as examples. Students were more eager to ask questions in class after labs had been run. These observations were consistent during all course offerings from both authors. Interviews with students indicated that the experiments truly did improve their understanding and provided a framework from which they were able to better analyze process control problems. The key improvements made for the second offering of the modified course were more detailed instructions for inductively designed labs, and efforts to reduce waiting times during thermal labs.

No direct assessment of any improvement in student learning was possible. For one instructor, the course was only taught one time. For the other instructor, the addition of these laboratories was concurrent with a change in textbook and course structure.

ADDRESSING LARGER CLASSES

Clearly, it is not feasible in all institutions to require all students to participate in a half-dozen lab exercises in small groups over the course of a semester. For larger classes, some options include in-class kits such as those developed by Moor and Piergiovanni,[13] or remote, Internet-based labs available at all hours, such as those developed by Henry.[12] One additional option takes advantage of newer equipment that is controlled via computer. By adding a remote video camera and using a remote access technology (such as Remote Desktop in Microsoft Windows), students can get familiar with the equipment in one hands-on lab exercise, and then use the remote access technologies to control the equipment in later labs. This paradigm emulates the experience of an industrial operator, where most of the control is performed by wire with only occasional visits to the equipment being controlled. Computer software could also be used to accomplish many of the objectives of laboratory experiences. Control-oriented simulation software is commercially available as a stand-alone software package (*e.g.*, Loop-Pro Trainer[19]) or as an add-on to MATLAB.[20] Either approach should be suitable as a substitute for some laboratory exercises.

CONCLUSIONS

Restructuring a chemical process engineering course to include significant elements of experiential learning seems to improve student learning. Inductively designing some of those exercises seems noticeably more effective at introducing new topics in process control than traditional lectures alone, as evidenced by the quality of classroom discussion as perceived by the instructors. Six laboratory exercises were developed within the context and schedule of a traditional lecture course, and were integrated into the course to improve student learning. Student feedback indicates students value the lab experiences, provided they do not perceive they are wasting time waiting for systems to reach steady-state.

REFERENCES

1. Silverstein, D.L., "An Experiential and Inductively Structured Process Control Course in Chemical Engineering," *Proceedings* of the 2005 ASEE Annual Conference & Exposition, ASEE, (2005) Also appeared as Silverstein, David L., "An Experiential and Inductively Structured Process Control Course in Chemical Engineering," *CACHE News*, **62**, Summer 2006.
2. Farrell, S., and R.P. Hesketh, "An Inductive Approach to Teaching Heat and Mass Transfer," *Proceedings* of the 2000 ASEE Annual Conference & Exposition, ASEE (2000)
3. Felder, R.M., and L.K. Silverman, "Learning and Teaching Styles in Engineering Education," *Eng. Ed.*, **78**(7), 674 (1988)
4. Lennox, B., and M. Brisk, "Network Process Control Laboratory," *Chem. Eng. Ed.*, **32**(4), 314 (1998)
5. Skiliar, M., J.W. Price, and C.A. Tyler, "Experimental Projects in Teaching Process Control," *Chem. Eng. Ed.*, **32**(4), 254 (1998)
6. Joseph, B., C. Ying, and D. Srinivasagupta, "A Laboratory to Supplement Courses in Process Control," *Chem. Eng. Ed.*, **36**(1), 20 (2002)
7. Ang, S., and R.D. Braatz, "Experimental Projects for the Process Control Laboratory," *Chem. Eng. Ed.*, **36**(3), 182 (2002)
8. Muske, K.R., "Simulation and Experiment in an Introductory Process Control Laboratory Experience," *Chem. Eng. Ed.*, **37**(4), 306 (2003)
9. Toghiani, H., R.K. Toghiani, D.O. Hill, and C. Wierenga, "Enhancement of Instrumentation and Process Control Studies at the Undergraduate Level," *Proceedings* of the 2000 ASEE Annual Conference & Exposition, ASEE (2000)
10. Clough, D.E., "The Integration of Laboratory Experience with a Senior Course in Chemical Process Instrumentation and Control," *Proceedings* of the Frontiers in Education Conference, Champaign-Urbana (1977)
11. Clough, D.E., "Bringing Active Learning into the Traditional Classroom: Teaching Process Control The Right Way," *Proceedings* of the 1997 ASEE Annual Conference & Exposition, ASEE (1997)
12. Henry, J., "Web-based Controls Laboratory Hardware and Software," <http://chem.engr.utc.edu/>
13. Moor, S.S., and P. Piergiovanni, "Experiments in the Classroom: Examples of Inductive Learning with Classroom-Friendly Laboratory Kits," *Proceedings* of the 2004 ASEE Annual Conference & Exposition, ASEE (2004)
14. Prince, M.J., and R.M. Felder, "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases," *J. Engr. Education*, **95**(2), 123 (2006)
15. Hesketh, R.P., S. Farrell, and C.S. Slater, "The Role of Experiments in Inductive Learning," *Proceedings* of the 2002 ASEE Annual Conference & Exposition, ASEE (2002)
16. Creative Engineering Web site, <http://www.reallabs.net>
17. Armfield Limited Web site, <http://www.armfield.co.uk>
18. Feedback Instruments Limited Web site, <http://www.fbk.com/>
19. Loop-Pro Trainer by Control Station, Inc., <http://www.controlstation.com>
20. Doyle, F.J., *Process Control Modules*, Prentice Hall PTR (2000) ❐

TESTING A CONSTRAINED MPC CONTROLLER
in a Process Control Laboratory

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Model predictive control (MPC) is a widely used control methodology in the chemical industry for the control of multivariable processes under constraints. Although the implementation of predictive controllers in chemical plants has been traditionally subcontracted to specialized companies, there is a need for the process control engineer to understand the algorithm for the purposes of maintenance and tuning and there is an increasing trend for in-house implementation of these controllers by process control engineers with limited control experience. Thus, there is a great incentive to familiarize chemical engineering graduates with this control methodology. Predictive control theoretical concepts are presented in different undergraduate control textbooks.[1-3] Also, although there are published experiments of multivariable controllers in undergraduate control laboratories,[4-6] undergraduate-level experiments of constrained predictive controllers based on linear models are less common.[7]

The experimental system discussed in this work is used in a process control laboratory course offered as a fourth-year elective in the chemical engineering undergraduate program at the University of Waterloo. The experiment involves the application of a constrained model predictive control algorithm for the control of a double pipe heat exchanger (DPHE). The elective laboratory course is composed of two main experiments: multivariable control of the DPHE described in the current paper and single variable temperature control in a stirred tank heater. Each of these experiments is conducted in two three-hour sessions. In addition, the course includes a weekly one-hour tutorial lecture in which theoretical concepts related to the experiments are covered, *e.g.*, topics on system identification, discrete control, and, more specifically, model predictive control. The presentation of MPC theory is done during four one-hour tutorial sessions and it includes a discus-

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sion of the output prediction equations, the analytical solution of the unconstrained case using least squares, the effect of tuning parameters such as weights, control, and prediction horizons, and a brief discussion about constrained optimization. Since it is challenging to deliver all the necessary theory of MPC in the tutorial hours, the students are provided with a clear and concise 10-page manual containing both theory and the experimental procedure[8] and they are referred to the material in the tutorial of the MPC toolbox in MATLAB[9] and to lecturer notes.

The experiment presented in this paper was tailored to illustrate several particular features of constrained MPC *vis-à-vis* other control methodologies such as decentralized control. First, the experiment is used to illustrate system identification, the concept of interaction in multivariable systems, and how this interaction varies with changes in operating condition due to the system's nonlinearity. Then, the experiment is used to demonstrate how the constrained optimization of the predictive controller can be used to effectively regulate the system at operating conditions where the interaction is very significant. Although one could claim that a nonlinear simulation of the system could be used to illustrate the capabilities of MPC, the implementation of the controller to a real system offers the unique opportunity to observe challenges that may be encountered in industrial practice. For example, the fact that different process models are obtained on different sessions suggests the occurrence of time-varying conditions, nonlinearity, valve stiction, and measurement noise. Furthermore, the fact that the students test the MPC on a real system adds significant credibility to the theoretical concepts. The constrained MPC optimization problem is given as follows:[9-10]

at each sampling interval k:

$$\min_{\Delta \mathbf{u}} \sum_{t=1}^{p} \left\| \mathbf{\Gamma}_i \left(\mathbf{y}(k+i|k) - \mathbf{r}(k+i|k) \right) \right\|^2 + \sum_{j=1}^{m} \left\| \mathbf{\Lambda}_j \Delta \mathbf{u}(k+j|k) \right\|^2 \quad (1)$$

subject to

processs constraints

Where y is the outputs prediction vector at interval k, **r** is the set point vector at interval k, and $\Delta\mathbf{u}$ is the vector of the manipulated variables at interval k. The matrices $\mathbf{\Gamma}_i$ and $\mathbf{\Lambda}_j$ represent the output and input weighting matrices for the MPC algorithm and p and m are the prediction and control horizon, respectively.

Another important feature of the experiment is that the controller has been implemented by interfacing a standard MATLAB MPC function through a LabView-based interface. This configuration offers the possibility in the future to easily change the constrained predictive controller based on linear models by other controllers that can be programmed in MATLAB, *e.g.*, nonlinear or adaptive predictive controllers. An additional consideration favoring the use of a LabView-based interface is that previous experiences with the MATLAB real time interface toolbox exposed limitations in controlling the sampling interval[11] whereas in LabView the sampling interval could be accurately controlled. Furthermore, the University of Waterloo has a license agreement with National Instruments that naturally motivated the use of this software/hardware combination.

The paper is organized as follows: Section 2 describes the chemical process and the hardware used in the experiment. Section 3 presents an overview of the LabView/MATLAB hybrid program created by the authors to interface with the process. Section 4 presents the experimental procedure used to perform the on-line testing of the constrained MPC controller. Section 5 presents the experimental results and the experience gained by the students following the experiment. Concluding remarks are presented in Section 6.

2. EXPERIMENTAL EQUIPMENT

The double pipe heat exchanger (DPHE) consists of six sections of concentric tubing set out as shown in Figure 1. Each section of the pipe is made of steel of approximately 122 in long. A heat transfer oil fluid, Therminol 55,[12] flows through the center tube (1 1⁄2 in) in all six sections. In the first three sections, saturated steam is supplied to the outer tubes (3 in) to heat the oil. In the latter three sections, tap water flows counter-currently to cool the oil. The cooled oil then flows to a 0.3 m^3 storage/surge tank from which it is recycled to the first section of the heat exchanger using a centrifugal pump. Four type-T thermocouples are located in the process unit to measure the inlet and outlet temperature of the oil and the tap water, respectively. Similarly, stainless steel vane-type flow meters are installed on the DPHE to measure the inlet oil and water flow rates. The oil flow is controlled using a ball valve whereas the water flow rate is controlled by

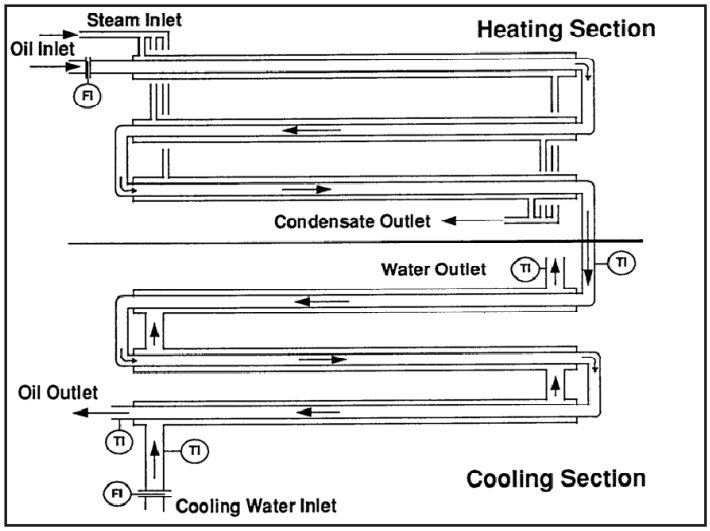

Figure 1. *Double pipe heat exchanger apparatus.*

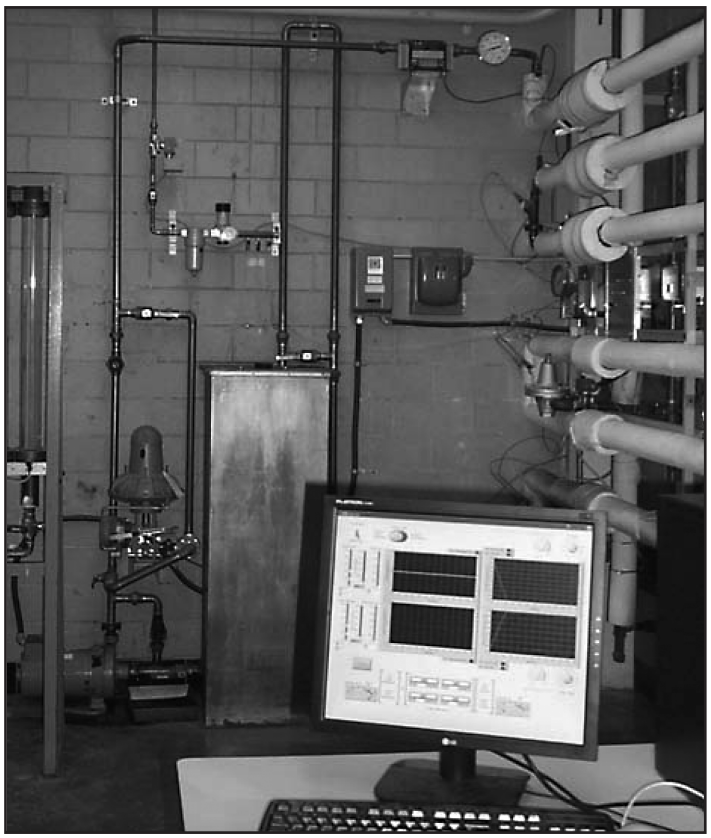

Figure 2. *DPHE process.*

a gate valve. The pressure of saturated steam is controlled using a manually operated globe valve and is measured by a local pressure gauge. All sections of the heat exchanger are insulated to prevent heat loss and for safety. Figure 2 presents a snapshot of the process. The hardware configuration used to interface the process with a PC was based on National Instruments interface devices.[13]

3. LABVIEW AND MATLAB— A HYBRID SOFTWARE INTERFACE

The role of the software interface in the process laboratory is to bridge process signals, human-machine interfacing (HMI), and the management of external data. LabView's wire and block programming[13] facilitated the use of visually informative dynamic plots, dials, and data entry for use as an HMI tool. The implementation of the MPC calculations in the LabView environment was expected to be laborious, however. Thus, it was decided that MATLAB(TM) along with its MPC add-on toolbox[9] is a more suitable computational environment for performing the MPC calculations. The new key feature in LabView software is the use of a MATLAB Script Node block that allows for wiring of variables to and from the LabView programming environment into an m-script text-based command line format of MATLAB. Details regarding the state-space based constrained MPC algorithm implemented in this work can be found in Bemporad, et al.,[9] and Maciejowski.[10] Figure 3 shows the graphical HMI developed for this experiment. As shown, it displays four x-y plots, mode selection switches, signal parameters, MPC parameters, and an MIMO Laplace transfer matrix process-model format. A copy of the LabView code developed by the authors is available upon request from <laricard@uwaterloo.ca>.

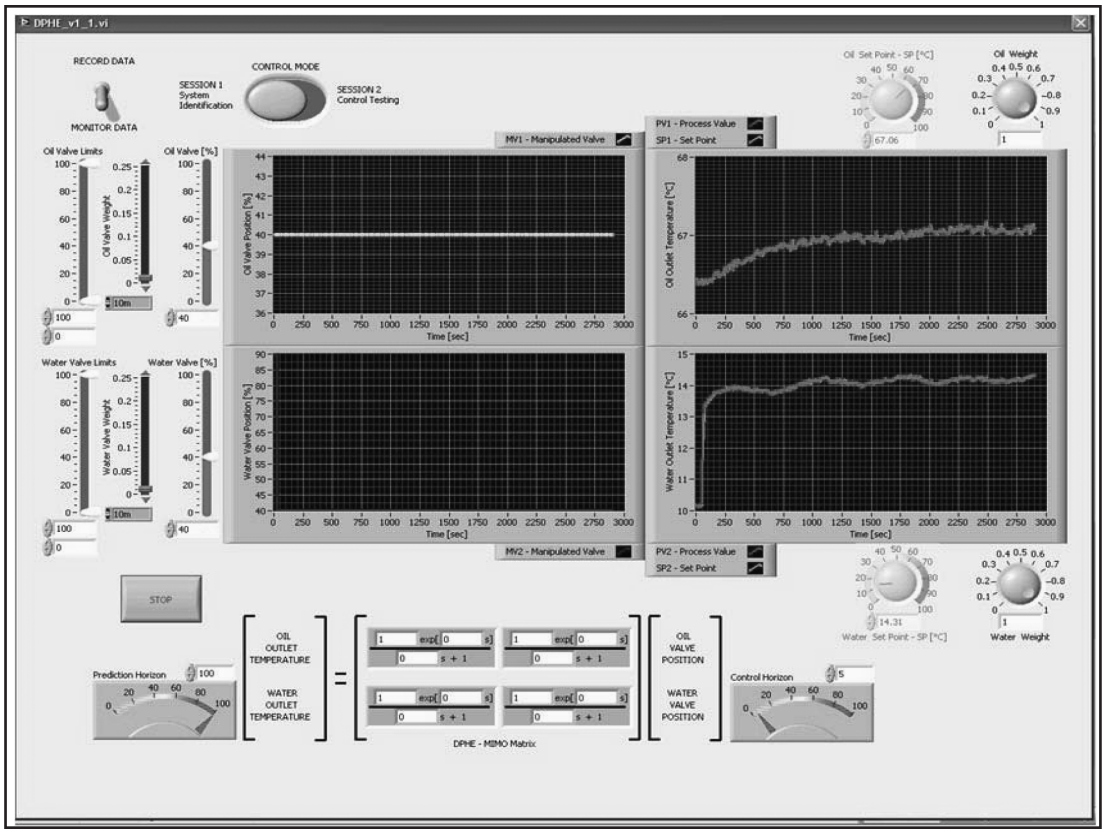

Figure 3. *HDI interface in the LabView/MATLAB program. The graphic displays show the DPHE response to a step change in the water valve from 90-40% of opening.*

4. EXPERIMENTAL PROCEDURE

Due to the length of the tests, the MPC experiment is divided into two three-hour laboratory sessions: a first part that involves models' identification and the second part that involves closed-loop control tests. For safety, the students and the lab instructor are required to wear protective glasses and insulated gloves during the lab sessions. The electrical equipment and the fluids are properly contained so as to prevent any contact between them.

4.1 Laboratory Session 1: System Identification

The goal in the first lab session is to obtain process data for the identification of dynamic models of the DPHE process. The oil and water flow rates at the inlet are used to control the oil and water temperatures at the outlet. Thus, four transfer function models that describe the dynamics between the water and oil valve and the oil and water temperature must be identified for this process. To identify each of these models, the students design a series of tests based on step changes on the input variables following a two-factorial design. The procedure to perform the step tests is available online.[8] The graphical display in Figure 3 shows a snapshot of the evolutions of oil and water temperature following a step change in the water valve from 90% to 40% of opening. From these graphs, the students are able to observe the effect of disturbances that may affect the process during the step tests, *e.g.*, changes in the inlet water temperature. Likewise, they can notice the interactions occurring in the process. Based on the exponential nature of the step responses, the students conclude that the process can be approximated by a set of First Order plus Time delay (FODPT) models. These models are used by the constrained MPC algorithm[9-10] in the second lab session to calculate the moves in the oil and water valves (inputs) that will drive the oil and the water temperatures toward a user-defined set point.

4.2 Laboratory Session 2: Control Testing

To commence the MPC closed-loop control testing, the DPHE is brought to an initial steady state. Students construct their own set point tracking and disturbance rejection experiments to validate their system identification and to gain intuition into the effect of different tuning parameters values such as weights and prediction horizons as defined in Eq. (1). Based on the results obtained from this session and discussion with the lab instructor regarding the closed-loop performance of the system, the students elaborate the final lab report for this experiment. Details on the experimental procedure to perform this test are available online.[8]

5. TYPICAL RESULTS AND DISCUSSION: EXPERIENCES GAINED BY THE STUDENTS

Figure 4 shows one of the set point tracking tests performed in the second session of the lab. As shown, both the water and the oil temperature smoothly track the set point signals. The water and the oil valves are manipulated by the MPC algorithm to reach the reference signals. The water valve, however, reached an input limit (60% of

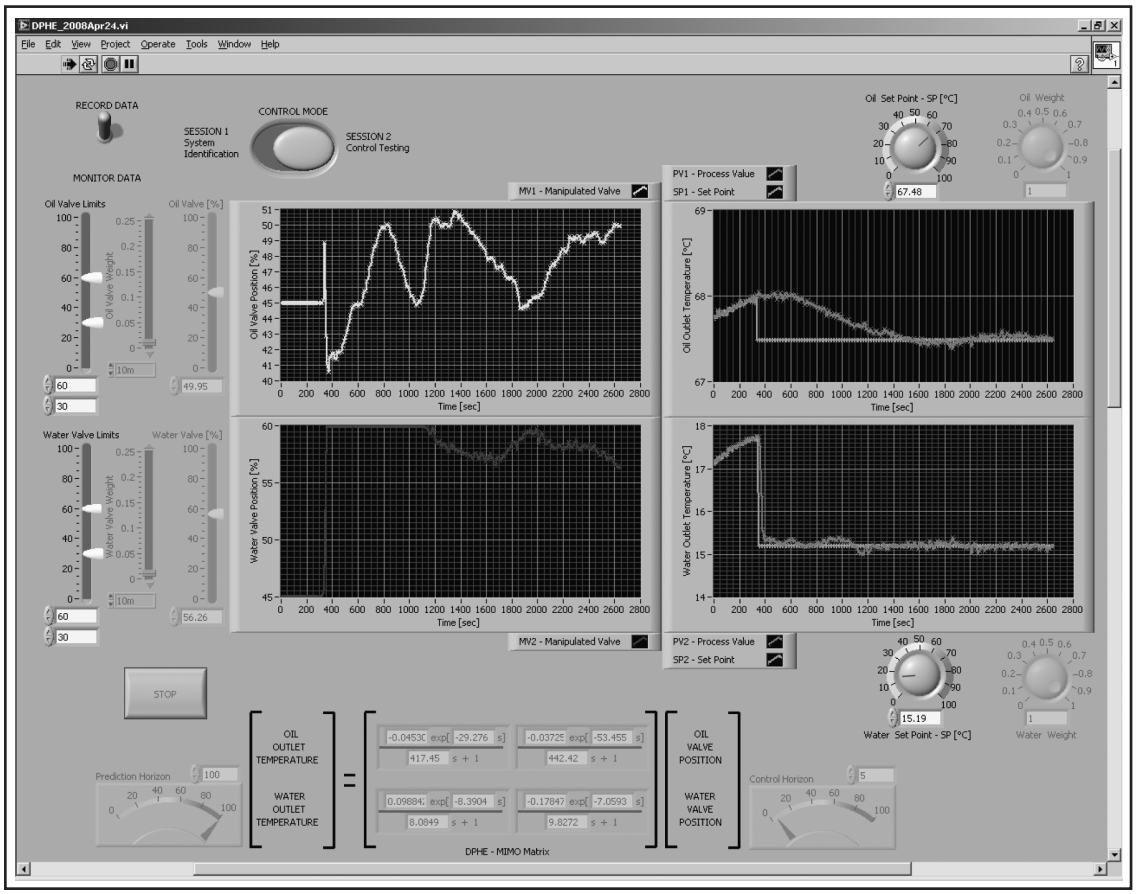

Figure 4. *Closed-loop performance in the DPHE: Constrained MPC test for a set point change in both the oil and water temperature.*

valve opening) for a period of time and then returned back to its feasible operating condition specified by the students. This result shows that the implemented constrained MPC algorithm works properly but it also demonstrates that the performance is limited by the presence of process constraints. Similarly, the controller performance-to-disturbance rejection is tested by closing for 350 seconds the steam valve that supplies steam into the process. Figure 5 shows the case where this disturbance test is performed in open loop and closed loop. The performance is judged by comparing the sum of square errors for the water and oil showing a 35% and 65% improvement for water and oil, respectively, obtained with the closed loop system as compared to open loop operation. In the event that one or both manipulated variables reach and remain at constraints, offsets will occur in the controlled variables. The instructor explains to students that the offsets in the two controlled variables can be altered, one vs. the other, by properly selecting the output weight matrix to be different from the identity matrix.

Upon completion of this laboratory, the students gain a number of practical and insightful experiences that can be categorized as experiential, analytical, and design oriented.

Experiential: Students gain experience in multivariable control of a typical chemical process, *i.e.*, a heat exchanger. This experiment evolved from a previous implementation that ran for several years and used an unconstrained MPC algorithm coded in a rudimentary DOS-based BASIC environment. To ensure that the new implementation will enhance the students' learning experience, an undergraduate student that is also one of the coauthors of this publication participated in the development of this project. Clearly, the key advantage of the new implementation is the ability to enforce constraints. In addition, in the earlier implementation, the graphical interface and the recording capabilities were very limited and the students could only manipulate the valve's set points in the identification test and the temperature set points in the closed-loop. With the new LabView/MATLAB implementation, the students use a graphical interface that shows the complete process response to a particular change, they can manipulate the MPC tuning parameters during the control testing session, and they can record up to 3.5 hours of process data. Many of these software and HMI improvements were introduced following the suggestions of the coauthor that had experienced the lab as a student.

In particular, the DPHE experiment allows the student to learn about nonlinear processes, the techniques frequently used for model identification and the performance of model-based control algorithms that are typically implemented in the industry for multi-

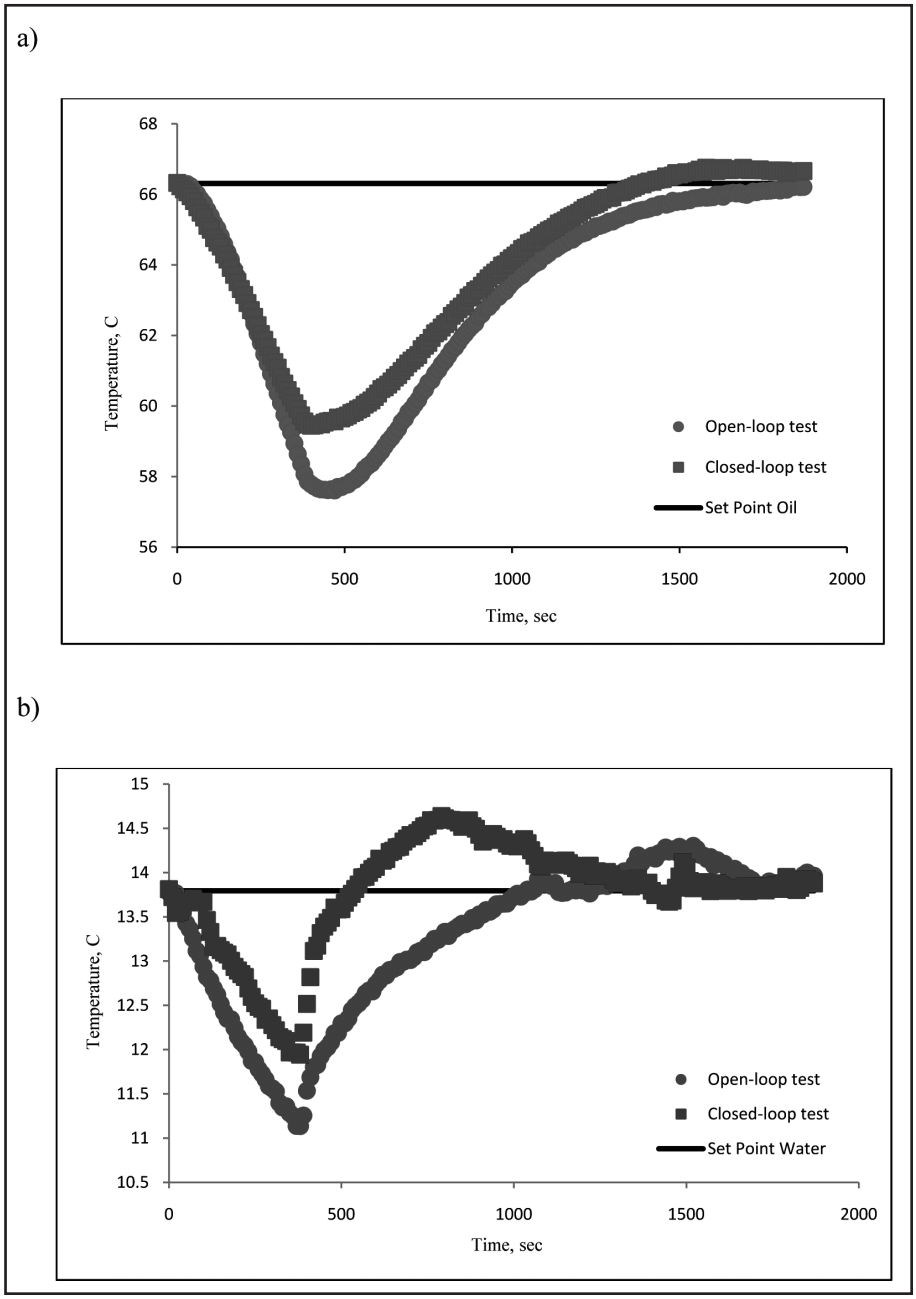

Figure 5. *DPHE response to a disturbance in the steam: a) oil response and b) water response.*

TABLE 1
RGA Analysis for the DPHE at Different Operating Points

Open-loop Tests	λ_{11}
Step tests 1 and 5	0.4827
Step tests 2 and 8	1.3006
Step tests 3 and 7	1.2603
Step tests 4 and 6	0.4724

variable control. The real-time operation of a physical system also allows for the development of intuition into background noise and system disturbances inherent in a real system. The challenges posed by noise and disturbances become evident when the student attempts to fit the collected noisy data at different valve positions to a linear FOPDT MIMO plant model. Moreover, Session 2 also shows that processes like the DPHE are challenging to control because they are highly nonlinear and show a high degree of variable interaction. This system's nonlinearity and interactions are evident in Table 1, which shows the RGA analysis estimated using the identified FOPDT around different operating conditions. As shown in this table, the first element of the RGA matrix (λ11) ranges from 0.48 to 1.3 depending on the selected operating point, whereas for an ideally linear system the RGA should remain constant for all operating points. In view of these systems' characteristics, one of the key challenges is to obtain process models that mimic the true process behavior and to select controller tuning parameters based on the identified dynamic behavior.

Another experience-based observation is that due to the open-loop time constants being relatively large (10-15 minutes), the students found that the identification experiments were somewhat lengthy. The waiting time was used for discussions about identification and control issues. Moreover, the students that performed the lab at the beginning of the term and that were not previously exposed to the MPC theory found it somewhat challenging to study this theory on their own. This was partially addressed by making available, at the early stages of the lab, the theoretical MPC principles in the manual pages and in the tutorial of the toolbox. Future planned improvements in this course include the development of questionnaires that must be answered during the lab experiment. Also, to further address the lack of theoretical background, the lecturer of the course is planning to deliver the fundamentals of the MPC theory at the beginning of the term.

Analytical: Students gain experience about data set analysis. The students find the dynamic model parameters by using nonlinear optimization where they minimize the sum of the square errors between the data collected in the first session and the model predictions. Addressing noise in the process data, solving the nonlinear optimization problem and obtaining meaningful process model parameters for each test are just a few of the challenges confronted by the student following the process model identification session.

During the second session of the lab, the students test the controller performance using different MPC tuning parameters. For example, they observe that increasing the weights on the movements of the manipulated variables produces a sluggish response with a large settling time.

To verify the importance of interaction, the students are instructed to implement a decentralized control strategy using the MPC algorithm by setting the off-diagonal process model

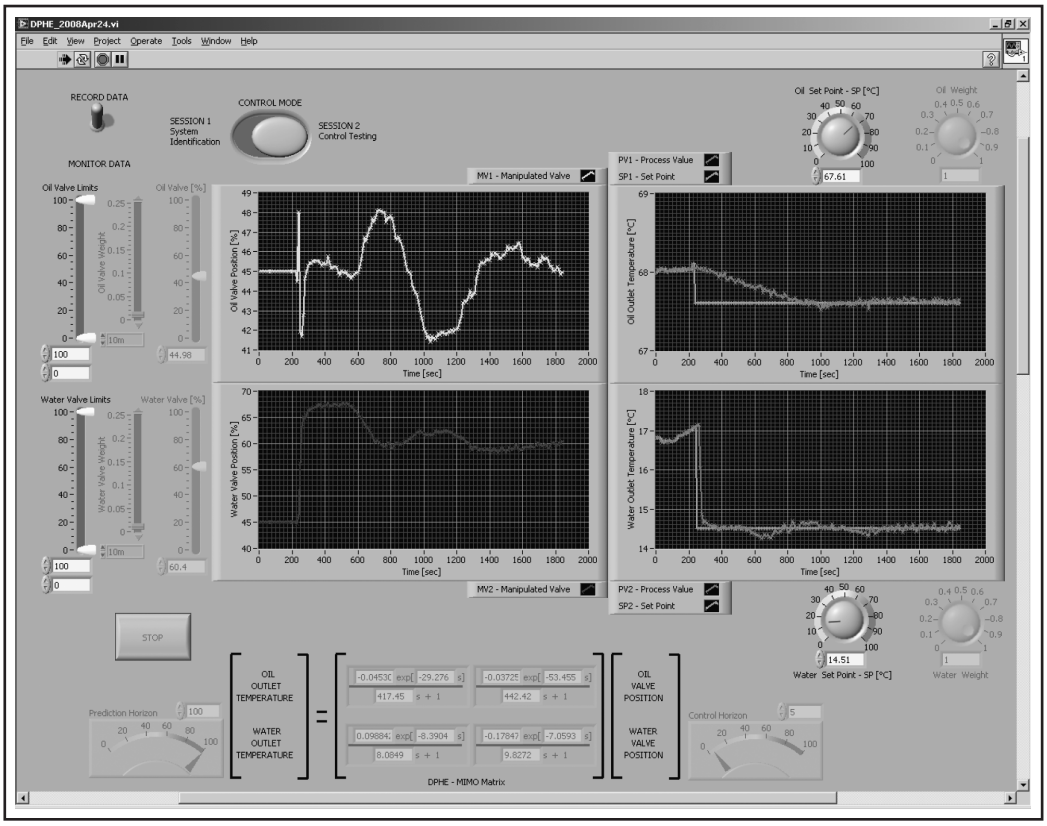

Figure 6. *Closed-loop performance in the DPHE: Unconstrained MPC test for a set point change in both the oil and water temperature.*

parameter gains to zero and testing a set point change in both outputs. Since this test generally results in closed-loop instability the students conclude that accounting for interaction is of utmost importance corroborating the need for a centralized multivariable MPC control strategy.

Design-oriented: From the results obtained in Session 1, the students realize that the process is highly nonlinear (see Table 1). Therefore, the students must be careful when defining the nominal operating condition for the process in the second part of the lab. That is, if they select an operating region for which the process model parameters do not accurately represent the process and the proposed set point changes to be tested are close to the process operating limits, then MPC will perform poorly resulting in input saturation and outputs far away from their corresponding set-point values. Thus, operability considerations must be addressed when estimating the process model parameters and the MPC tuning parameters. On the other hand, the students can also analyze the trade-offs when either considering or ignoring constraints in the input variables. Figures 4 and 6 shows the process response to a set point change when the MPC algorithm takes into account input constraints (Figure 4) and when it does not (Figure 6). As shown in these figures, the oil temperature requires a longer time to reach the reference signal when the input's constraints in the MPC algorithm are active (Figure 4). Therefore, the students learn from this test that process limitations can drastically affect the system's closed-loop performance and that process design considerations, such as process constraints, have a direct impact on the controllability of the process.

The learning outcomes presented in this section were assessed based on both the discussions between the laboratory assistant and the students and from the final laboratory report.

6. CONCLUDING REMARKS

This paper presented an implementation of a linear constrained MPC in a process control laboratory at the University of Waterloo. Upon completion of this experiment, the fourth-year chemical engineering students are expected to appreciate the capabilities of MPC over conventional feedback controllers. From the experiment, the students conclude that a decentralized strategy for highly interactive processes such as the DPHE cannot provide a satisfactory performance as it was demonstrated in the lab and that an MPC controller is more suitable for this task. Likewise, they conclude that the selection of the MPC parameters plays a key role in the closed-loop performance. The students also learn that constraints significantly affect the closed-loop process performance and that care must be given to the selection of the operating point in a process. They also learn to appreciate that data analysis and relatively accurate models are essential in the development of a model-based control strategy. In summary, the DPHE experiment represents an educational and practical tool that shows the challenges usually involved in the industrial deployment of MPC strategies to multivariable processes with high degree of interaction and in the presence of constraints. The University of Waterloo operates a large co-operative program where students spend at least one term per year in industry. Many of the students that have been exposed to MPC applications in their co-operative terms have expressed that the current experiment have offered them a unique opportunity to experience and understand the design and implementation of this advanced controller.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Waterloo Engineering Endowment Fund (WEEF) and the Department of Chemical Engineering at the University of Waterloo for their financial support.

REFERENCES

1. Seborg, D.E., T.F. Edgar, and D.A. Mellichamp, *Process Dynamics and Control*, 2nd Ed., John Wiley & Sons, USA (2004)
2. Marlin, T.E., *Process Control: Designing Processes and Control Systems for Dynamic Performance*, 2nd Ed., McGraw Hill, USA (2000)
3. Bequette, W., *Process Control: Modeling, Design and Simulation, Prentice Hall*, New Jersey, USA (2003)
4. Joseph, B., C. Ying, and D. Srinivasagupta, "A Laboratory to Supplement Courses in Process Control," *Chem. Eng. Ed.*, **36**(1) 20 (2002)
5. Long, C.E., C.E. Holland, and E.P. Gatzke, "Experimental Air-Pressure Tank Systems," *Chem. Eng. Ed.*, **40**(1) 24 (2006)
6. Rusli, E., S. Ang, and R. Braatz, "A Quadruple Tank Process Control Experiment," *Chem. Eng. Ed.*, **38**(3) 171 (2004)
7. Gatzke, E.P., E.S. Meadows, and F.J. Doyle III, "Model Based Control of a Four-Tank System," *Computers and Chem. Eng.*, **24**, 1503 (2000)
8. <http://www.eng.uwaterloo.ca/~hbudman/>, accessed May 14, 2009
9. Bemporad, A., M. Morari, and N.L. Ricker, Model Predictive Control Toolbox(TM) 3, The Mathworks, Natick, USA (2009)
10. Maciejowski, J.M., *Predictive Control with Constraints*, Prentice Hall, Great Britain (2002)
11. Ricker, N.L., "Using MATLAB/Simulink for Data Adquisition and Control," *Chem. Eng. Ed.*, **35**, 286 (2001)
12. <http://www.therminol.com/pages/products/55.asp> accessed Mar. 10, 2009
13. <http://www.ni.com/labview/> accessed March 10, 2009 ❐

A SIMPLE REFRACTION EXPERIMENT
for Probing Diffusion in Ternary Mixtures

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Diffusion in mixtures is one of the most important molecular transport processes in the understanding of mass transfer operations in chemical engineering,[1, 2] and it is the fundamental phenomenon underlying chemical processes ranging from mass transport in living cells and separations to corrosion. Consequently, reports in the literature on chemical education have frequently focused on simple experimental demonstrations for diffusion in liquids.[3-11] Here, we describe an experiment based on Wiener's method[12] for measuring one-dimensional diffusion in ternary aqueous solutions and incorporate several new features that provide an opportunity for students to practice computer calculations.

The method relies on using refraction of laser light from the concentration gradient near a solvent-solution interface. Past reports[7, 10, 11] have used this optical technique for undergraduate-level demonstrations of diffusion in a physical chemistry laboratory. In these past reports, diffusion of single solutes such as KCl or CsCl in liquids such as water or glycerol was examined experimentally to demonstrate one-dimensional diffusion in binary mixtures as well as the impact of solvent viscosity on the diffusion coefficient. We show that the optical technique described in literature can be also used to analyze diffusion in ternary mixtures of simple species, namely KCl and sucrose in water.

In the experiment described here, we chose mixtures of KCl and sucrose but the method can be extended to other solutes. In other work, we have explored the application of this method to solutions of linear and globular polymers.[13] KCl and sucrose, in addition to being inexpensive, have various other advantages. For example, well-established literature exists on diffusion studies of these chemicals in water.[14-17] The rapid diffusion (~90 minutes) of both species makes them conducive for a laboratory session, and the materials are nontoxic for students. Furthermore, transparent solutions with a stable solution-water interface can be easily prepared for both KCl and sucrose.

From an educational perspective, the laboratory experiment described in this paper has many useful features. It demonstrates to students how a molecular scale process manifests

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itself into macroscopic observables and provides them a visual display of the time evolution of the concentration profile (Figure 1), which is governed by the diffusion equation in one dimension.

$$\frac{\partial c_A}{\partial t} = D_{AB}\frac{\partial^2 c_A}{\partial z^2} \quad (1)$$

New elements are incorporated in the implementation of the experiment to give students' practice in skills such as digital capture and digitization of experimental data, plotting and baseline correction, familiarity with simple statistical concepts such as Gaussian distributions, and finally multivariable, nonlinear data fitting using common software such as Excel™. The experiment can also be extended to reinforce a variety of concepts ranging from simple statistical and error analysis to more advanced concepts of mass transfer such as the importance of cross-diffusional contributions in mixtures. Thus, the experiment is suitable for incorporation into the curriculum at various stages depending on the emphasis placed on the different aspects of the experiment. For example, it can be used as an introductory hands-on learning opportunity at a freshman or sophomore level in chemical engineering or related fields of environmental engineering, biochemical engineering, physics, and physical chemistry to emphasize the mathematical and computational aspects of the experiment with lesser emphasis on diffusion theory. Alternatively, it can be incorporated in a chemical engineering laboratory at a junior or senior level in coordination with the typical course on mass transfer theory that covers topics of diffusion in binary and ternary systems.

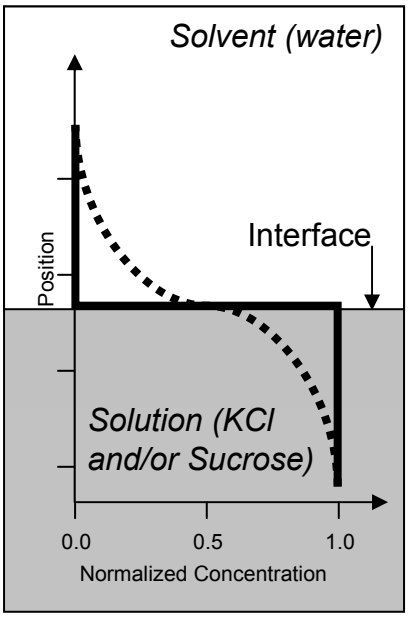


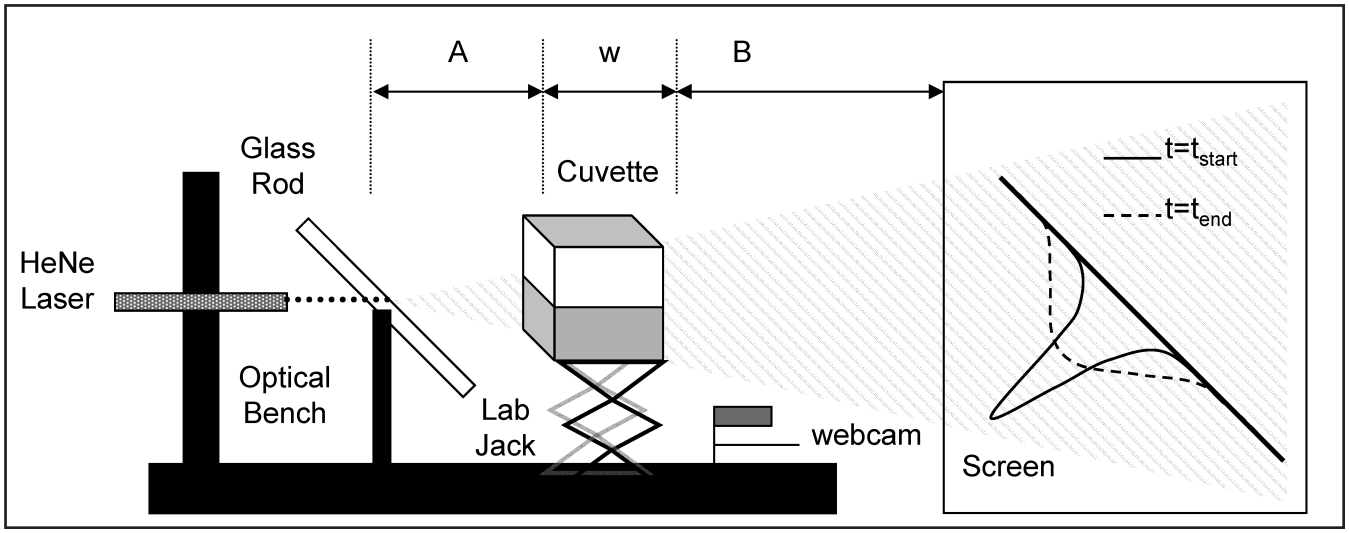
Figure 1. (right) *Schematic representation of initial step concentration gradient (solid line) and concentration profile as diffusion of solute occurs across the interface (dashed line).*

Figure 2. (below) *Schematic representation of experimental arrangement and the optical deflection curve.*

LABORATORY DESCRIPTION

Experimental Plan

A schematic of the experimental setup is shown in Figure 2. A 12"×18" aluminum breadboard (MB1218 from Thorlabs, Newton, NJ: cost~$200) was used as the platform. The various components shown in Figure 2 could be fixed to the breadboard using the threaded holes, which is convenient as it makes the whole assembly portable. An inexpensive alternative is to use any flat surface such as a table or countertop. A 5 mW laser diode module (31-0508 from Coherent Inc., Wilsonville, OR: cost~$180) was held using a laboratory stand and clamp. It was fanned through a commonly available laboratory glass rod (OD=3mm) to create a thin diagonal band of laser light at 45 degrees to the horizontal to scan several depths in the cuvette simultaneously. We found that a laser leveler readily available from home improvement stores can be a reasonable inexpensive substitute to the laser diode. As a safety measure, students were explicitly warned to avoid direct eye contact with the laser beam. The distances A and B shown in Figure 2 were adjustable and could be used to manipulate the magnification of the projected optical curve on the screen.



In our setup, the distances A and B were approximately 13 cm and 50 cm, respectively. A rectangular refraction cuvette (09417107 from Cynmar, Carlinville, IL: cost ~$5) measuring 60×30×62mm was initially half-filled with a solution of KCl and/or sucrose purchased from Fisher Scientific. De-ionized water used in experiments was obtained from an EasyPure UV system (Barnstead, IA). A 0.2μm filter in this system removed particulate matter. The ternary solutions studied contained a total of 10wt% solute in the following ratios: (A) 25% KCl, 75% sucrose; (B) 50% KCl, 50% sucrose; (C) 75% KCL, 25% sucrose. In addition, experiments were also performed with binary mixtures containing 10wt% of either KCl or sucrose.

Initially, the cuvette was raised or lowered using a laboratory jack until the air-solution interface (marked by a discontinuity) could be located on the screen. The experiment was carried out by carefully pouring the solvent (water) upon the aqueous mixture (KCl and/or sucrose) in the cuvette to create a sharp boundary (solid line in Figure 1). The diffusion of the solute molecules from concentrated solution into the water phase with time leads to a decrease in the sharpness of the interface (dashed line in Figure 1). As a consequence, the refractive index gradient at the boundary changed with time and a skewed Gaussian curve developed on the screen as the beam traversed the mixture-water interface. Over time, diffusion of the solute caused the optical curve to become broader and smaller in peak height. The optical trace was projected on a screen (a box covered with blank paper or graph paper) and was photographed using a digital Web camera (Rosewill RCM-32301 from Newegg, Whittier, CA: cost ~ $30) at regular intervals of time. A free software (Automouseclicker18, Version 2.10) allowed automatic image capture with the Web camera at pre-determined intervals by clicking the capture button for the camera.

THEORY

At any particular time during the diffusion process, the gradient in the concentration ($\partial c/\partial x$) near the interface results in a gradient in the refractive index ($\partial n/\partial x$). For binary mixtures of a single solute species in a solvent this gradient is best described by the Gaussian function[7]:

$$\frac{\partial n}{\partial x} = \frac{\Delta n_o}{\sqrt{4\pi D\left(t - t_0\right)}} \exp\left(-\frac{\left(x - x_0\right)^2}{4D\left(t - t_0\right)}\right) \qquad (2)$$

Here Δn_o represents the difference in the refractive index contrast between the aqueous solution of the solute (KCl or

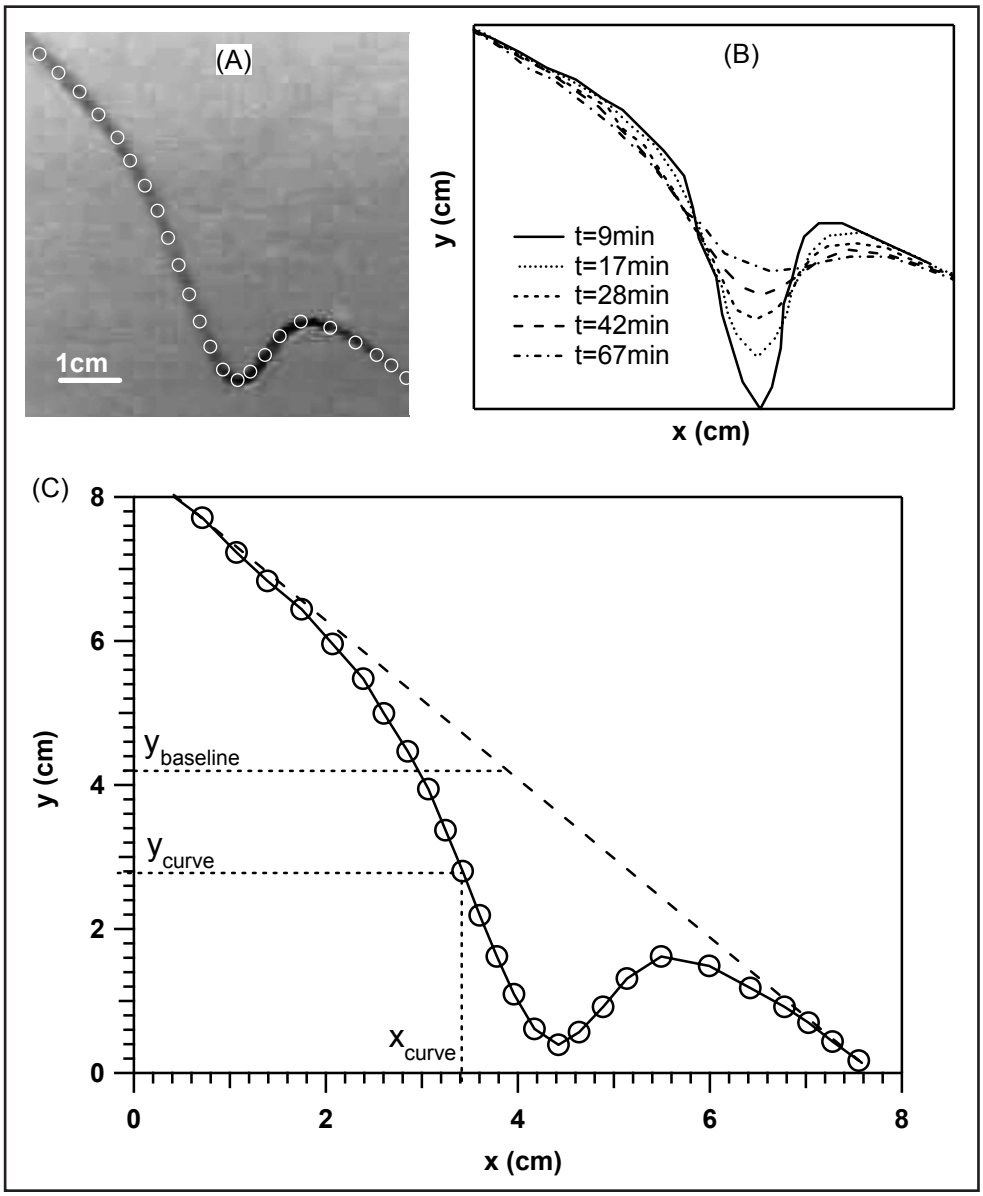


Figure 3. *(A) Image of the optical deflection curve illustrating the digitization procedure. (B) Digitized curves at different times. (C) Plot illustrating the baseline correction procedure.*

sucrose) and water at the initial time (t_0). The value of Δn_o depends on the initial weight fraction of the solute and is typically available in literature[19] or can be measured using a refractometer. D is the diffusion coefficient of the solute species.

In the case of ternary mixtures of two species α and β, we used a simplified extension of Eq. (2) for the overall gradient in refractive index.

$$\frac{\partial n}{\partial x} = \frac{\Delta n_{o\alpha} z_\alpha}{\sqrt{4\pi D_\alpha (t-t_0)}} \exp\left(-\frac{(x-x_0)^2}{4D_\alpha (t-t_0)}\right) + \frac{\Delta n_{o\beta} z_\beta}{\sqrt{4\pi D_\beta (t-t_0)}} \exp\left(-\frac{(x-x_0)^2}{4D_\beta (t-t_0)}\right) \quad (3)$$

where the initial refractive index gradients ($\Delta n_{o\alpha}$, $\Delta n_{o\beta}$) for each species are scaled by the relative composition in solution using fractions (z_α, z_β). It should be noted that the implicit assumption in Eq. (3) is that the individual species in the mixture diffuse independently of each other. The non-zero contribution of cross-diffusional terms in multi-component mixtures is well known in research literature.[15-17, 20-22] Neglecting cross-term diffusion coefficients is reasonable within the context of an undergraduate laboratory experiment, however. This simplifying assumption keeps the data analysis simple and introduces relatively small error for the case of 10wt% total solute concentration.

DATA ANALYSIS AND RESULTS

Figure 3A shows a typical optical deflection projected on the screen. As indicated in the figure, by selecting points along the deflection curve, the experimental data can be digitized with respect to an arbitrary origin. Use of digitizing software provides an opportunity for students to become proficient at extracting data from scientific charts and plots, which is a skill that can also be useful in other contexts when students need to perform data analysis using published literature. Digitizing software widely available from the World Wide Web can be used (*e.g.*, shareware license products such as Datathief™, Grab It! Graph Digitizer™, Graph Digitizer Scout™ or open source products such as Engauge Digitizer). The use of this software typically requires importing the image file obtained from the Web camera, defining the origin and maximum values for x- and y- axes using the software interface, and finally obtaining the coordinates via mouse-click at different points along the deflection curve. The software captures the location of each mouse-click and provides a table of coordinates that can be imported and analyzed in spreadsheet or data-fitting software. As an alternative to digitization with software, coordinates can be read from an image of the deflection curve superimposed on a graph paper and recorded into a spreadsheet. This approach rapidly becomes laborious, however, when several curves have to be analyzed and also does not promote the use of computational tools.

Figure 3B shows a collection of the digitized curves at various times during the diffusion process demonstrating the broadening of the optical deflection curve with decreasing peak height. The skewed nature of the curve is corrected by subtracting the linear baseline from each point (Figure 3C) and plotting $y(=|y_{curve}-y_{baseline}|)$ vs. x ($=x_{curve}$). Since the y-coordinate is directly proportional to the refractive index gradient, Eq. (2) modified with scaling constants K_1 and K_2 describes the dependence of y on position and time as

$$y(x,t) = K_1 \frac{\partial n}{\partial x} = \frac{K_1 \Delta n_o}{\sqrt{4\pi D (t-t_0)}} \exp\left(-\frac{K_2 (x-x_0)^2}{4D(t-t_0)}\right) \quad (4)$$

K_1 and K_2 are experimental constants and incorporate the magnification of the optical deflection via distances A and B (Figure 2) and the refraction of the laser light by the acrylate cuvette wall.

Use of digitizing software provides an opportunity for students to become proficient at extracting data from scientific charts and plots, which is a skill that can also be useful in other contexts.

Prior to characterizing the ternary systems, the scaling factors K_1 and K_2 were determined experimentally using only KCl in water (in an undergraduate laboratory, this step may be completed beforehand by a teaching assistant). Data was collected using 10%, 15%, and 23% solutions of KCl. For each solution, the value of Δn_o was taken from literature and Eq. (4) was used to fit the y(x,t) data as a function of both variables for a common set of parameters K_1, K_2, x_0, t_0, and D_{KCl} using least squares fitting in Excel™ using the Solver add-in. The average K_1 and K_2 values of these runs were used as constants in all further experimental studies. As a check, the binary diffusivity of sucrose in 10% solution in water was also measured. Table 1 shows that there is a good agreement between the measured binary diffusivity values for KCl and sucrose with those found in literature.

In the case of ternary mixtures of KCl-sucrose-water, the total solute concentration was held constant at 10wt% and relative ratio of KCl and sucrose (z_α:z_β) in the solution was

TABLE 1

Substance	D(cm²/s) (from fit)	D(cm²/s) (from literature[17])
KCl[a]	1.81×10^{-5}	1.87×10^{-5}
Sucrose[b]	4.45×10^{-6}	4.77×10^{-6}

[a] $n_o(KCl) = 1.215\times10^{-4} c_o(g/L)+1.3334$
[b] $n_o(sucrose) = 1.601\times10^{-4} c_o(g/L)+1.3318$
using literature data[19]

varied (0.25:0.75, 0.5:0.5, 0.75:0.25). From the deflection curves obtained (Figure 4) for each solution, the relative fractions (y_α,y_β) of the individual solutes were obtained using a fit to Eq. (5).

$$y(x,t) = K_1 \frac{\partial n}{\partial x} = \frac{K_1 \Delta n_{o\alpha} z_\alpha}{\sqrt{4\pi D_\alpha (t-t_0)}} \exp\left(-\frac{K_2 (x-x_0)^2}{4D_\alpha (t-t_0)}\right) + \frac{K_1 \Delta n_{o\beta} z_\beta}{\sqrt{4\pi D_\beta (t-t_0)}} \exp\left(-\frac{K_2 (x-x_0)^2}{4D_\beta (t-t_0)}\right) \quad (5)$$

During this regression of the experimental data, the diffusivity and the refractive index increment (Δn_o,D) were held constant for both species while the parameters (z_α, z_β, x_0, and t_0) were changed. The optical curve at several different times was regressed using least-squares fitting in Microsoft Excel™ using the Solver add-in (illustrative worksheets are available at <http://www.eng.usf.edu/~vkgupta/diffusion.html>). From Table 2, we can see that the predicted values of relative ratios of the individual solutes agree quite well with the known solution concentration.

SUMMARY

The experimental method outlined above offers a rapid, visually instructive, and easy method for studying diffusion. It also functions as a pedagogical tool for practicing skills such as data acquisition, graphing, and regression using common software such as Excel™. The laboratory experiment reinforces concepts in chemical sciences such as molecular basis of macroscopic properties and diffusional mass transfer alongside mathematical concepts of partial differential diffusion equation, the Gaussian form of the concentration gradient, and multivariable functions. Aspects such as error analysis of the data can be incorporated by having the students consider consequences of not choosing sufficient points or sufficient care during digitization or using only a few time intervals. Although we assumed that the cross-term diffusivities were not significant, the experiment outlined above can be extended to higher (>10%) weight fractions of KCl/sucrose mixtures where the cross-term diffusivities do become important and predicted relative compositions for the solutes begin to deviate significantly from solution conditions. An investigation in this direction could then easily form the basis of mini-projects for student teams.

ACKNOWLEDGMENTS

This research was carried out with the support of the Department of Chemical and Biomedical Engineering at the University of South Florida. Graduate support in the form of a teaching assistantship from NSF grant on Curriculum Reform (EEC-0530444) to CAC and BDM is also acknowledged.

TABLE 2

Composition ratio in a 10% solution of KCl and Sucrose	Composition ratio from fit	
KCl:Sucrose	z_{KCl}	$z_{sucrose}$
0.75:0.25	0.72	0.28
0.50:0.50	0.52	0.48
0.25:0.75	0.23	0.77

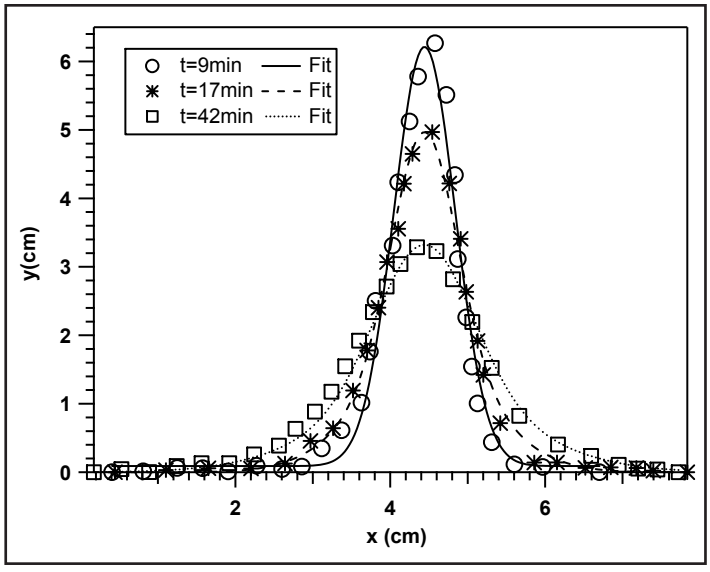


Figure 4. *Experimental data with fit using Eq. (5).*

REFERENCES

1. Bird, R.B., W.E. Stewart, and E.N. Lightfoot, *Transport Phenomena*, 2nd Ed., John Wiley & Sons, Inc., New York (2006)
2. Geankoplis, C.J., *Transport Processes and Unit Operations*, 4th Ed., Prentice Hall, Upper Saddle River, NJ (2003)
3. Bevia, F.R., and M. Del Mar Olaya, "Mass Transfer Experiment Determination of Liquid Diffusion Coefficients," *Chem. Eng. Ed.*, **36**(2), 156 (2002)
4. Clifford, B., and E.I. Ochiai, "A Practical and Convenient Diffusion Apparatus. An Undergraduate Physical Chemistry Experiment," *J. Chemical Education*, **57**(9), 678 (1980).
5. Conard, C.R., and H.E. Bent, "Diffusion of Potassium Permanganate as a Lecture Demonstration," *J. Chem. Ed.*, **46**(11), 758 (1969)
6. Fate, G., and D.G. Lynn, "Molecular Diffusion Coefficients: Experimental Determination and Demonstration," *J. Chem. Ed.*, **67**(6), 536 (1990)
7. King, M.E., R.W. Pitha, and S.F. Sontum, "A Laser Refraction Method for Measuring Liquid Diffusion Coefficients," *J. Chem. Ed.*, **66**(9), 787 (1989)
8. Kwon, K.C., T.H. Ibrahim, Y. Park, and C.M. Simmons, "Inexpensive and Simple Binary Molecular Diffusion Experiments," *Chem. Eng. Ed.*, **36**(1), 68 (2002)
9. Linder, P.W., L.R. Nassimbeni, A. Polson, and A.L. Rodgers, "The Diffusion Coefficient of Sucrose in Water. A Physical Chemistry Experiment," *J. Chem. Ed.*, **53**(5), 330 (1976)

10. Rashidnia, N., R. Balasubramaniam, J. Kuang, P. Petitjeans, and T. Maxworthy, "Measurement of the Diffusion Coefficient of Miscible Fluids Using Both Interferometry and Wiener's Method," *Int. J. Thermophysics*, **22**(2), 547 (2001)
11. Sattar, S., and F.P. Rinehart, "Diffusion of CsCl in Aqueous Glycerol Measured by Laser Refraction: A Physical Chemistry Experiment," *J. Chem. Ed.*, **75**(9), 1136 (1998)
12. Wiener, O., "Darstellung gekrummter Lichtstrahlen und Verwerthung derselben zur Untersuchung von Diffusion und Warmeleitung," *Annals of Phys. Chem.*, **49**, 105 (1893)
13. Mankidy, B.D., C.A. Coutinho, and V.K. Gupta, "Probing the Interplay of Size, Shape, and Solution Environment in Macromolecular Diffusion Using a Simple Refraction Experiment," *J. Chem. Ed.* (in press)
14. Jamshidi-Ghaleh, K., M.T. Tavassoly, and N. Mansour, "Diffusion Coefficient Measurements of Transparent Liquid Solutions Using Moire Deflectometry," *J. Physics D: Applied Physics*, **37**(14), 1993 (2004)
15. Kim, H., and G. Reinfelds, "Isothermal Diffusion Studies of the Water-Sucrose-Potassium Chloride System at 25.deg," *J. Solution Chemistry*, **2**(5), 477 (1973)
16. Kim, H., G. Reinfelds, and L.J. Gosting, "Isothermal Diffusion Studies of Water-Potassium Chloride-Hydrogen Chloride and Water-Sodium Chloride-Hydrogen Chloride Systems at 25 °C," *J. Physical Chemistry*, **77**(7), 934 (1973)
17. Reinfelds, G., and L.J. Gosting, "Measurements of Isothermal Diffusion at 25 Deg with the Gouy Diffusiometer on the System Water-Sucrose-Potassium Chloride," *J. Physical Chemistry*, **68**(9), 2464 (1964)
18. automouseclicker <http://www.murgee.com/auto-mouse-clicker/>
19. Washburn, E.W. (Ed.), *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology*, Knovel (2003)
20. Curtiss, C.F., and R.B. Bird, "Multicomponent Diffusion," *Industrial & Engineering Chemistry Research*, **38**(7), 2515 (1999)
21. Haugen Kjetil, B., and A. Firoozabadi, "On Measurement of Molecular and Thermal Diffusion Coefficients in Multicomponent Mixtures," *J. Phys. Chem. B*, **110**(35), 17678 (2006)
22. Lightfoot, E.N. Jr., E.L. Cussler Jr., and R.L. Rettig, "Applicability of the Stefan-Maxwell Equations to Multicomponent Diffusion in Liquids," *AIChE Journal*, **8**, 708 (1962) ❒

CLOSING THE GAP BETWEEN PROCESS CONTROL THEORY AND PRACTICE

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There is increasing pressure on the manufacturing industries around the globe to meet new tougher demands and regulations.[1] Higher product quality, expensive raw materials, larger production volume, environmental and safety regulations, global economy, and other factors have forced industries to rethink the way manufacturing is executed.

Process control or automation is a tool that can be employed by companies to deal with these challenges. Therefore, the demand for people well-educated in process control, especially in chemical-based processes, is increasing. Therefore, universities must also rethink the way process control is taught.

The Experiential Learning[2] theory establishes that learning is a cycle that begins with experience, continues with reflection, and finishes with actions that become concrete experience for reflection. In summary, the learning cycle includes concrete experience, reflective observation, abstract conceptualization, and active experimentation steps, in that order. This means that the learning process is enhanced with hands-on activities[3] in which teams of students[4] act on the fundamentals.

Based on the teaching needs for process control, the Chemical Engineering Department of the University of Puerto Rico at Mayagüez (UPRM) is tackling the challenge of modifying the material taught in the classroom and including hands-on

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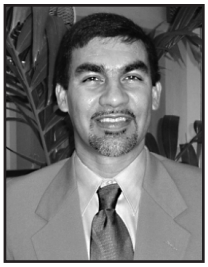

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Eng. Edwin Velázquez *has a bachelor's degree in electrical engineering from University of Puerto Rico at* Mayagüez *and an M.B.A. from University of Phoenix. He was the founder of Automation Technologies, Inc., a system-integration engineering company focused on process control automation projects for the bulk chemical industry. He has taught the control practice part of the course in several occasions.*

experience with real industrial control systems and industry practices. The new approach at UPRM integrates process control theory, where all the basic and indispensable concepts and rationale are discussed, with a unique real practice of chemical process control. This paper describes the changes in the course material, the infrastructure to support the innovation, and the hands-on project. The main feature of the project is the use of real industrial technologies and practices to ensure a rookie engineer has a solid basis in process control.

MODIFICATION OF COURSE MATERIAL

A survey of process control course syllabi demonstrates that the typical teaching method used consists of lectures on introduction to process control; principles-based modeling of processes, sensors, and actuators; stability analysis using several techniques; control loop tuning; cascade; feed forward; and maybe an additional strategy if time allows. Most of the process control textbooks are written with a large focus on these topics[5,6] including, in some cases, material related to control practice and standards.

At UPRM, the course has been aligned with a recent trend of several textbooks[7-9] that orient the course toward more practice experience. Table 1 presents the syllabus established to accomplish this alignment; it can be seen that the course starts with control practice topics including laboratory work, real-life example, and seminars offered by an industry expert. This material is followed by a reduced portion of the use of mathematical concepts to support the real application of control. In parallel, the students work in the innovative hands-on experience with an industrial control system (more details ahead).

During the semester the students dedicate 45 hours to classroom time, plus the corresponding time for the exams, plus approximately 35 hours to complete their corresponding tasks for the special project. Therefore, the students dedicate on average eight hours per week to this course, which is taken by the students in their fifth year of the bachelor's degree. This course is taught both Spring and Fall semesters to typically between 45 and 60 students.

The final grade consists of four individual exams (three partials and one final), which have a weight of 75% of the grade. The remaining 25% corresponds to the special project, which most of the time is a group grade. The professor reserves the right to compensate or penalize the student for performance that differs significantly from the rest of the team, however. The objective with the change in material content is to familiarize students with basic experience in most of the

TABLE 1
Organization of Course Topics and Tasks

Hours	Course Topics	Project Tasks (executed out of the class period)
2	Introduction to Process Control	
1		Discussion of project, formation of teams and workgroups
1		Project Management
1	Basic Components of Control Systems - Sensors	Seminar 1: Validation (3 hrs)
2	Basic Components of Control Systems - Actuators	Seminar 2: Distributed Control Systems (3 hrs)
2	Basic Components of Control Systems -Controllers	Preparation and hand-in of Gantt chart (3 hrs)
1	Discrete Control, Boolean Logic	Training with assigned operation and presentation to show how to use the equipment (5 hrs)
1	Control Design (P&ID and SAMA)	
5	Example	
First Partial Exam		
3	Modeling of Dynamic Systems • Balances • Dynamics • Simulation	Progress report by each of the workgroups: process modeling, interface, control algorithm, and validation (5 hrs)
2	Process Parameter Estimation • Hints for experiments	Execution by each workgroup of corresponding tasks. (Industry-expert support is provided) (10 hrs)
3	Design of Single-Loop Feedback Control Systems	Meeting between workgroups and progress evaluators (1 hr)
1	Tuning of Feedback Controllers	Completion of modeling task (5 hrs)
Second Partial Exam		
2	Cascade Control	Completion of interface (5 hrs)
1	Ratio control	Completion of control algorithm and experiments (5 hrs)
2	Feed forward	Completion of validation process and demonstration of performance of the controlled operation (5 hrs)
Third Partial Exam		

The deliverable is a cluster of students aware of the issues of hardware implementation, control strategy selection, and process understanding. Therefore, they are able to contribute more to their employers from Day One of being hired.

issues concerning automating real manufacturing operations but maintaining the basic concepts. Students are exposed to issues such as communication protocols between accessories, integration of software, tuning of real controllers, industry standards, and validation of processes and systems. In the end, the student should be able to connect the control practice with control fundamentals. The deliverable is a cluster of students aware of the issues of hardware implementation, control strategy selection, and process understanding. Therefore, they are able to contribute more to their employers from Day One of being hired—which contrasts sharply with the current situation, in author Velazquez's experience, in which newly hired engineering graduates need from six to 12 months to acquire enough experience to start contributing to companies.

DETAILS ON COURSE MATERIAL

The course begins with students visiting the laboratory to see the industrial control system and the sensors and actuators installed in the different equipment, getting a first-hand view of the control of one of the operations of the industrial control system. The course continues with lectures describing characteristics of sensors, actuators, typical communication protocols, control system specifications, and control strategies. This first section then wraps up with designing control loops (*e.g.*, PID, discrete, dead band) for a chemical process. These control loops are designed and represented through two industry standard formats: one called SAMA (Scientific Apparatus Marketing Association drawings) as well as the well-known Process and Instrumentation Diagram (P&ID).[5] This is the first encounter by students with control loops. The lectures are enhanced with experiences and practical details and aspects of implementation of a process control project from process control engineers. The main idea is to provide students with as much knowledge as possible of real-life applications, such as control logic, for safety of humans and processes. A first individual exam with the same focus as the material covered is administered at this point.

The second part of the semester is focused on the fundamentals of control. The topics include 1) modeling of processes (low-order transfer functions), actuators, and sensors using empirical data; 2) closed-loop transfer function and stability; and 3) tuning. For the modeling of the process including the sensors and actuators, the students perform experiments using the control system, collect the raw data, and fit the low-order transfer functions. For this task, they use the graphical method but they could also use Matlab™ or Excel™. The material offered in the classroom comes directly from the textbook and is enhanced with control practice details especially for the tuning part. This is followed by another individual exam.

The third part then focuses on cascade, feed forward, and ratio control, if time permits. The main idea here is to guide students to learn when and how to implement these strategies to improve the strategies learned before. This objective is basically the same as used in textbooks. A third individual exam is administered after these last topics are covered.

In summary, the students should have learned practical aspects for a process control project, the basic feedback control strategy and its practical aspects, and three additional strategies designed to enhance the basic feedback strategy, all along with the hands-on project.

DESCRIPTION OF THE HANDS-ON PROJECT

The project starts early in the semester by dividing the process control group into five teams. Each team is then subdivided into four working groups. Each working group is then assigned one of four tasks: 1) modeling of the assigned operation; 2) control loop design, implementation, and tuning; 3) control interface; and 3) hardware and software validation. The last two tasks come from the control practice in industry. Each team is provided with a scope-of-work document that describes the project assigned and the objectives, the hardware and software available, and the requirements for grading.

The first task for each team is to use basic project management techniques to prepare a Gantt chart of the remaining tasks to achieve the desired scope, including the overall deadline for the entire project. For this, either the instructor or an expert from the industry (preferred) lectures on project-management basics. Before students start working with the system, additional seminars and workshops are offered in control system configuration and operation and computerized process systems validation. Typically, two or three industry experts help us with the seminars and the direct support to students.

Another requirement is that students must demonstrate to the instructor that they know how to run the particular unit operation and the control system. For this, each team visits the unit operation laboratory and the control room to familiarize themselves with the different accessories, and gather information on how to run their operation.

After that, the group in charge of modeling prepares the procedure to generate and collect the adequate dynamics data for the low-order transfer function. At the same time, the group in charge of control loops designs the different loops through the SAMA drawings and prepares the P&ID drawings. The group in charge of the interface must collect information from the other groups to design the interface. At this point the four working groups must hand in a progress report, which should include the dynamics data and the model of the operation. For the progress as well as the final report, all of the working groups of each team should communicate with each other to ensure each working group has any information required from the other working groups so that the work can be continued and all the details are included in the final report. This interaction is captured in Figure 1.

The project continues with the implementation of the interface and the control loops. During this period, several control experts from local system integration companies coach the students. This approach is similar to the mentoring approach used by Kavanagh and Crosthwaite.[6] Once everything is programmed, the entire group must run experiments in the automated system. The experiments must include at least a step change in set point and one disturbance. The student must characterize the performance of the control system using the standard criteria taught in class such as overshoot and decay ratio.

In parallel, the validation group, which at this point should have prepared the validation document, executes it, collecting data from the other working groups. After this, the four working groups prepare a final collective report that must be handed in by the deadline.

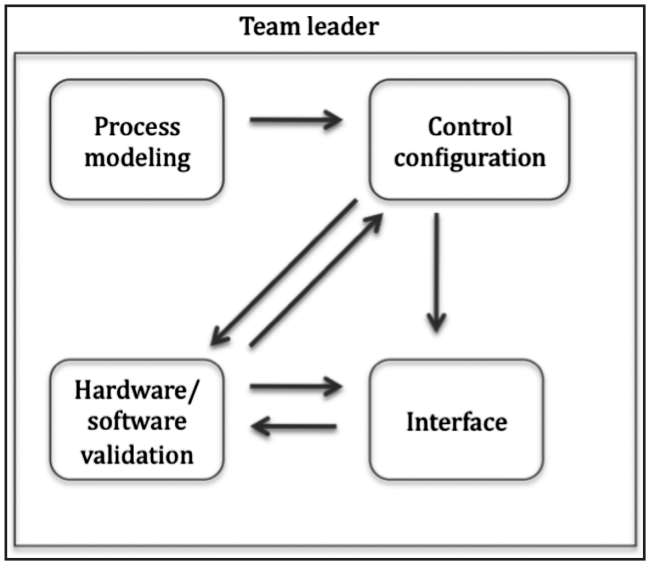

***Figure 1**. Interaction of working groups under the supervision of a team leader.*

The project implementation follows an identical project implementation life cycle to projects currently implemented in industry, to make this experience as valuable as possible. As can be deduced from the above description, the students must employ project-management techniques, prepare progress reports, have project status meeting between the students from each working group and the professors, and in some cases work in interdisciplinary environments.

The interdisciplinary environment is simulated by including in the teams students from electrical engineering who are pursuing a specialization in process control. This experience is typically done only during the Spring semester.

At the project completion, an open house is coordinated sometimes with industry leaders to give the students the opportunity to present and discuss their projects with future employers and professional partners. This exposition to industrial representatives also gives the university an opportunity to get industry feedback in terms of the latest trends and future industrial requirements, in order to continuously focus the projects to fulfill the industrial requirements.

CONTROL TECHNOLOGY AT THE LABORATORY

The infrastructure to support this innovation consists of a control room in the unit operations laboratory, which houses two industrial process control systems identical to the ones currently used in the bulk chemical processing industries. One control system (DeltaV from Emerson Process Management) consists of the controller, a 24V power supply, three analog input cards, one analog output card, one discrete input card, one discrete output card, one fieldbus card, one main administrative computer, and two workstation computers.

The other control system (PCS7 from Siemens) consists of the controllers, the power supply, two analog cards (input, output), and two discrete cards (input, output). This system uses profibus digital communication between the controller and the communication cards.

Five unit operations are connected to the systems: 1) a cooling tower, 2) a chemical reactor, 3) a distillation column, 4) a heated tank and level control, and 5) a heat exchanger. The cooling tower has three industrial pneumatic control valves and a variable frequency driver as actuators. In addition, it has three industrial RTDs (resistance temperature device) to measure the air inlet temperature, the water inlet temperature and the air outlet temperature. With these devices, there are four control loops: 1) air inlet temperature, 2) water inlet temperature, 3) water outlet temperature, and 4) air outlet temperature.

The heated tank and level control apparatus has two control valves, one for water inlet flow rate, and another for steam flow rate. To control the water outlet temperature, the

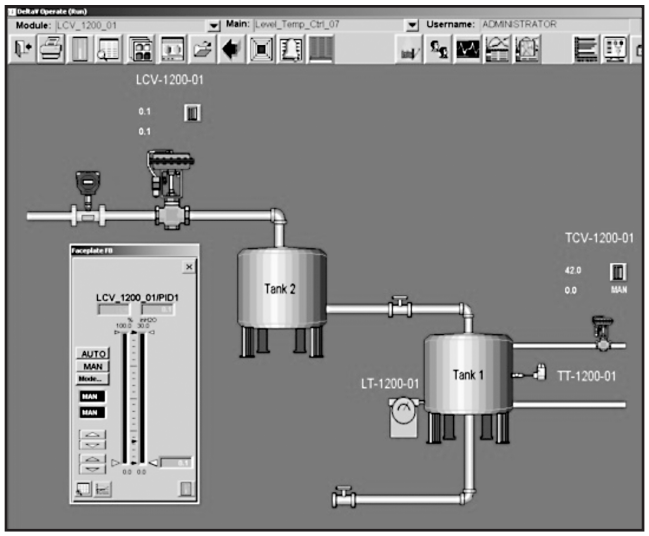

Figure 2. *Example of interface.*

apparatus has an RTD, and for the level it has an industrial pressure cell.

Figure 2 depicts an example of the interface the students developed for the heated tank. They used the symbols provided by the controller software, which are the same they would use or see if they were working in a company.

The heat exchanger also has two industrial pneumatic valves; one for steam flow rate and another for water flow rate. An RTD is installed at the exit of the heat exchanger for the control of the water outlet temperature. An analog flow meter at the entrance is used for the control loop of the water total flow rate through the heat exchanger.

The chemical reactor has two control valves; one is electronic while the other is fieldbus. Each control valve is used to manipulate the flow rate of each of the reactants. In addition, the reactor has four RTDs, two analog flow meters, and an analog pH meter. The pH meter is to control the outlet concentration (conversion) and the flow meters are for the total flow rate (residence time).

The distillation column has two pumps; one for the reflux flow and one for the feed flow. Each of these flows goes through a flow meter. In addition, the column has three control valves; one (fieldbus pneumatic) for the reflux rate, one (electronic) for the feed rate, and one (pneumatic) for the condenser water flow rate. The last actuator is a solid-state relay connected to the heating device of the boiler to manipulate the heat supplied to the solution. The output variables (temperature at the top and bottom plates) are measured with RTDs.

One additional component of the control infrastructure is the software called PI from OSIsoft, which is designed to collect data from industrial control systems. This software allows students to transfer their raw data from the historian of the control systems to spreadsheets like Excel. Once the data is transferred to the spreadsheet, the student can use all of the features of the spreadsheet to compute many different values and prepare plots. The software is installed at a server connected to the university network so that the students can access the data from any computer in the university.

To facilitate the availability of experienced process engineers for class lectures or support, a virtual classroom with videoconference capabilities has been implemented. This permits colleagues from industry to interact with students directly from their respective industrial sites without abandoning their working areas. Students receive the lectures or suggestions in real time and they are able to see, hear, and interact—questioning and clarifying doubts with their virtual professor at their regular class time.

IMPACT ON THE STUDENTS

The course modification was first implemented in Spring 2004 and since then it has transformed approximately 150 chemical engineering and 30 electrical engineering students. Many of these students have used experience from the project in their jobs. In some cases, the students have been the leaders in automation projects of several manufacturing operations (Spring 2008) even as early as in their first six months.

Table 2 presents the average, the maximum, and the minimum of the final grades for the Spring semesters before and after Spring 2004 (when the innovation was first implemented). As can be seen, the semester average after 2004 (75 pts) is 11% higher than the average before 2004. The maximum has increased substantially and the passing percentage has been higher, too. After 2004, withdrawals have been zero, which suggests that the students are more motivated to try until the end even if the grades are not too encouraging.

TABLE 2
Grade Distribution Before and After the Innovation

	Spring 1998	Spring 1999	Spring 2002	Spring 2003	Spring 2004	Spring 2006 I	Spring 2006 II	Spring 2007	Spring 2008
Avg	69.0	52.8	72.6	73.3	65.6	77.8	82.0	71.2	77.0
Max	81.1	89.4	91.9	92.3	81.6	92.0	96.8	95.9	95.0
Min	42.7	17.2	52.1	25.0	21.4	54.5	64.2	52.0	48.0
Pass %	95.0	77.5	87.5	93.1	72.2	88.9	96.9	95.0	90.9
W		4			2				

Looking at the individual exams under the new scheme, however, specifically exams 2 and 3 (related to the understanding of the fundamentals), it can be seen that the students are still earning similar grades as before. The reasons stem from the fact that the change described herein was aimed at modifying the material offered in the classroom and providing the students with hands-on experience with a real industrial control system. Independent of the reason, this provides another opportunity to improve the course once more, by incorporating a strategy to strengthen learning of fundamentals using the very same special project.

During the Spring semester, as mentioned above, students from both departments, electrical and chemical engineering, work together in the project. The dynamics between the students is similar to the one that develops in industry. This interaction helps the students with their interdisciplinary skills, which is one of the outcomes required by ABET (Accreditation Board for Engineering and Technology). Table 3 describes the outcomes that this innovation in process control teaching and learning impacts.

Most of the students do enjoy working with the project and see the value of the approach. Even the teaching of the course is more interesting, from the instructor perspective, especially since it allows the professor to get involved in the project with the students as they develop it during the semester. Many students comment after completing the project that it was a great experience and that they would have preferred to spend more time in the project to go deeper and gain more value out of the experience. Comments from industry professionals are very encouraging and supportive, too. Comments like "Finally, a project that teaches hands-on experience to the students" are heard from them.

The feedback from students has been valuable to keep fine-tuning the changes, including the current scheme of the course. This helps students reduce their initial stress caused by a topic quite different from the core courses of chemical engineering. The students are more motivated to take the course when compared with those that received or are receiving the classical teaching approach.

CONCLUSIONS

The teaching of the course since 2004, although more demanding on the professor, has been more interesting than in previous years. Most of the students enjoy and appreciate the project and most of them improve their opinion about process control as the semester progresses. The industry has been very supportive and consistently has considered the approach very innovative and of positive impact for them.

This approach not only provides practical experience in the process control engineering field but also provides a valuable visualization of the practical applications of all the theory learned. It also stimulates the students to continue with their careers, as there is a direct association of the theory learned and the future use of this knowledge in their professional careers.

The teaching of standards of industrial process control implementation and the experience acquired by implementing the projects complement the theoretical knowledge and help the students visualize and value all the theory learned. Also, the project implementation experience helps students to develop other important skills for their future professional lives, such as: project management, time management, presentation skills, leadership, work under pressure, and documentation and coordination between multidisciplinary groups. This project strongly supports the ABET outcome list.

One issue with the current approach is the time the students spent on the class and the number of credits received. The benefits the students receive, however, especially the solid ground on which to start their careers, outweigh the issue of no proper credit recognition, which can be addressed administratively. Finally, the implementation of the modifications presented here could mean a greater contribution for industry in general and, even more important, for the career of young, new engineers.

ACKNOWLEDGMENT

The authors are grateful of the support of Abbott Laboratories, Merck Co., Pfizer, Emerson Process Management, OSIsoft, INDUNIV (local industrial group), Air Products,

TABLE 3
ABET Outcomes That the New Innovation Impacts

1.	An ability to apply knowledge of mathematics, science, and engineering.
2.	An ability to design and conduct experiments, as well as to analyze and interpret data.
3.	An ability to design a system, component, or process to meet desired needs.
4.	An ability to function in multidisciplinary teams.
5.	An ability to identify, formulate, and solve engineering problems.
6.	An ability to communicate effectively.
7.	Recognition of the need for, and an ability to engage in, lifelong learning.
8.	An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.
9.	Recognition of basic leadership skills.

Automation Technologies, and Invision Engineering in the development of the required infrastructure.

REFERENCES

1. Clements, C., *Manufacturing Control Systems: A Unified Solution for the Life Sciences Industry,* August 2008, <www.pharmpro.com>
2. Demirkan, H., and Ö.O Demirbaş, "Focus on the Learning Styles of Freshman Design Students," *Design Studies*, **29,** 254 (2008)
3. Felder, R.M., "A Whole New Mind For a Flat World," *Chem. Eng. Ed.*, **40**(2), 96 (2006)
4. Oakley, B.A., D.M. Hanna, Z. Kuzmyn, and R.M. Felder, "Best Practices Involving Teamwork in the Classroom: Results From a Survey of 6435 Engineering Student Respondents," *IEEE Transactions on Education*, **50**(3), 266 (2007)
5. Smith, C.A., and A.B. Corripio, *Principles and Practice of Automatic Process Control*, 3rd Ed., John Wiley and Sons, Inc., NJ (2006)
6. Seborg, D.E., T.F. Edgar, and D.A. Mellichamp, *Process Dynamics and Control*, 2nd Ed., John Wiley and Sons, Inc., NJ (2004)
7. Svrcek, W.Y., D.P. Mahoney, and B.R. Young, *A Real-Time Approach to Process Control*, John Wiley and Sons, Inc., NJ (2000)
8. Luyben, W.L., *Plantwide Dynamic Simulators in Chemical Processing and Control*, Marcel Dekker, Inc. (2002)
9. Altmann, W., *Practical Process Control for Engineers and Technicians*, Newnes (2005)
10. Kavnagh, L., and C. Crosthwaite, "Triple-Objective Team Mentoring: Achieving Learning Objectives with Chemical Engineering Students," *TransIChemE, Part D, Education for Chemical Engineers*, **2**, 68-79 (2007) ❐

METSTOICH

Teaching Quantitative Metabolism and Energetics in Biochemical Engineering

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Biochemistry is one of the important foundation courses in a biochemical engineering curriculum. It provides a basic introduction of cellular metabolism to engineering students to teach them how raw materials can be converted into valuable metabolic products by microorganisms in various bioprocesses. Teaching metabolism in biochemical engineering courses normally adopts the traditional "biochemistry approach." Students are presented with a number of reaction pathways that make major cell components (*e.g.*, protein, RNA, DNA, lipids, cell walls) as well as major catabolic products using a qualitative description. Traditional chemical engineering courses, however, focus on product yield, selectivity, reaction rate, and reactor/process design. It is similar for biochemical engineers that product yield, biomass yield, and ATP yield are important parameters for bioreactor design. All these goals, if applied to a biochemical system, require a quantitative knowledge of metabolism. Therefore, a quantitative description in metabolism can complement the major skill base of engineering students and is more consistent with the overall philosophy or learning outcomes of an engineering degree.

As a subset of system biology, metabolic engineering focuses on the metabolism of one organism. It is the practice of purposeful modification of metabolism using recombinant DNA technology along with mathematical analysis to optimize genetic and regulatory processes within the cell. This leads to the modification of the cell's properties to achieve a desirable objective.[1-4] Metabolic Flux Analysis (MFA, also known as metabolite balancing, metabolic flux balancing, etc.), is a practical tool for understanding and analyzing metabolic pathways, pathway interaction, and control. Varma and Palsson[5] suggested that there are five major applications for MFA, namely: 1) to quantify metabolic physiology, 2) to simulate and interpret experimental data, 3) to analyze metabolic pathways for metabolic engineering, 4) to optimize cell culture medium, and 5) to design and optimize bioprocesses. MFA is an analytical tool developed based on stoichiometric network models,[6] and it is assumed that those metabolic fluxes are in steady state when compared with growth and other processes. Unlike simulations based on mechanistic models that require detailed enzyme kinetic data, MFA is used to analyze the metabolic flux map and only requires metabolic reaction pathway details and stoichiometry, growth metabolism, and several strain-specific parameters. MFA determines a domain of stoichiometrically allowable flux distributions.[5] Even if several restrictions are enforced, for complete metabolite balancing of a cell, a very large amount of flux data needs to be analyzed to accurately represent the interactions between the various metabolic pathways. Practically, such analysis is assisted by specifically designed software packages that simulate the metabolic networks.

The analysis provided by MFA is also good for demonstration of the quantitative aspects of metabolism to students. Most analytical software packages, however, are developed for research purpose and mainly focus on pathway control (*i.e.*, metabolic control analysis, MCA). Metstoich was initially developed to focus on teaching metabolism and to link practical biochemical engineering parameters with metabolic flux analysis.

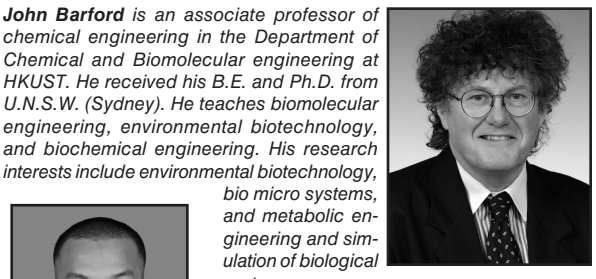

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TABLE 1
Parameters as Input and Output for Various Calculation Modes in Metstoich

Parameters	Problem Types			
	(a) Theoretical Y_{XS}	(b) Experimental Y_{XS}	(c) Predefined $Y_{X/ATP}$	(d) Experimental Y_{XS} with Predefined $Y_{X/ATP}$
(1) Cell compositions	Input	Input	Input	Input
(2) Glucose usage for energy generation process	Input	Input	Input	Input
(3) P/O ratio	Input	Input	Output	Output
(4) ATP efficiency	Input	Output	Input	Output
(5) Y_{XS}	Output	Input	Output	Input
(6) $Y_{X/ATP}$	Output	Output	Input	Input

EXISTING SOFTWARE PACKAGES

To explore the physiological properties of biological systems, a system of equations must be solved. Such a task can be easily done with the aid of modern personal computers and metabolic engineering software packages. Some important and/or widely used software packages are:

GEPASI 3[7-8] is a widely used free biochemical reactions simulation software package. GEPASI simulates the kinetics of biochemical reaction systems and provides functions such as metabolic control analysis (MCA), elementary mode analysis (EMA), optimization, and parameter fitting. The last version of GEPASI released was 3.30 in September 2002. COPASI[9] was developed based on GEPASI with different simulation techniques, optimization routine, etc. Jarnac (a.k.a. Scamp II)[10] simulates the steady state and transient behavior of metabolic pathways and calculates all coefficients for MCA.

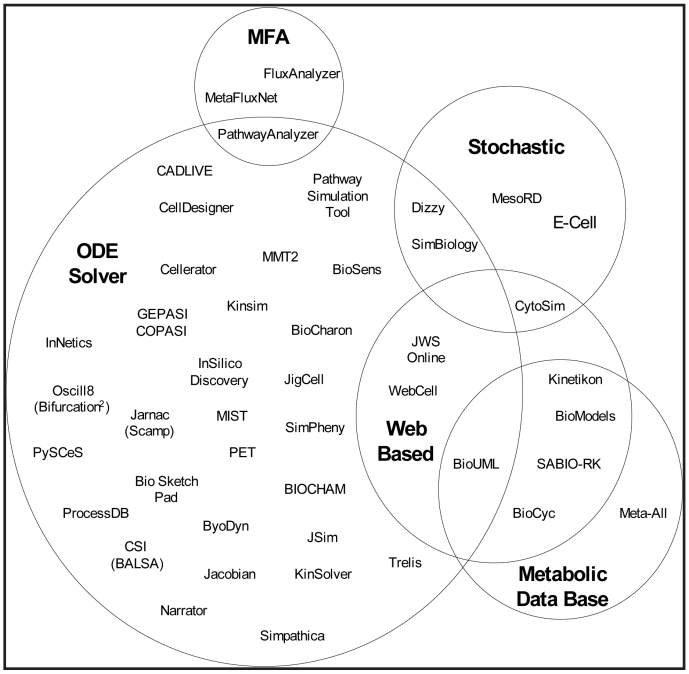


Figure 1 (left). *Some existing metabolic engineering software packages/projects.*

E-Cell[11] is an object-oriented, whole-cell simulation software package. MIST[12] performs dynamic simulations, stoichiometric calculations, and MCA. JWS Online[13] is an Internet-based metabolic simulator with collections of several metabolic models, and it can provide MCA to analyze the simulation results. KINSIM[14,15] is a rate equation-based numerical simulator and it was used for the simulation of enzymatic reaction system kinetics. FluxAnalyzer[16] is a MATLAB package with GUI for stoichiometric analysis of metabolic networks. It can provide functions such as MFA, flux optimization, topological features detection, and pathway analysis. In one of the more extensive examples, Klamt, et al.,[17] carried out a metabolic flux analysis on Purple Nonsulfur Bacteria by using FluxAnalyzer. This model involved 30 of the most important catabolic branchpoint-metabolites (intermediate metabolites to which at least three reactions are linked) and 41 catabolic reactions—1 for growth rate, 25 for central metabolic pathways, and 7 for photosynthesis, cyclic electron transport during photosynthesis, respiration, ATP synthesis, and maintenance. The model also involved 46 anabolic reactions using the stoichiometries presented in Neidhardt, et al.[18]

Except for FluxAnalyzer, all above simulation packages focus on the dynamic behavior of metabolic pathways. They require reaction kinetics as input and some of them can even perform metabolic pathway analysis such as MCA.

Other than the above-listed software packages, there are many packages/projects developed or under development. Figure 1 summarizes part of the metabolic engineering software packages/projects found. Most of them are ODE solvers, some of which can perform sensitivity analysis (MCA). Some, however, were developed for various purposes, such as:

- *CellDesigner[19] is for gene-regulatory and biochemical networks.*
- *Cellerator[20] is a Mathematica package designed for modeling with automated equation generation. It was designed with the intent of simulating signal transduction.*
- *InNetics[21] was developed for genomic-based drug discovery.*
- *The JigCell project[22] explores the cell physiology from the scope of molecular regulatory networks.*

There are two trends for metabolic software development.

The first trend is using visual tools to allow users to construct pathway models. The second is the development of Web-based applications. Nowadays, the Internet is already part of daily life and Web-based applications are a good choice, especially for database projects to collect and share data.

The common advantage of these packages is that you can input any model to the package for analysis. Their practical use for engineering purposes, however, is limited and is not their primary purpose. They do not address issues of energetics and ATP usage, the production of biomass yield, etc.

METSTOICH

Metstoich was initially developed for teaching purposes[23-24] and is based on the metabolism of a specific yeast, *S. cerevisiae*.[25] Metstoich includes the following major pathways: 1) central metabolic pathways, such as glycolysis, tricarboxylic acid (TCA) cycle and pentose-phosphate pathway (PPP); and 2) biosynthetic pathways. The central metabolic pathways serve to provide precursors for biosynthetic pathways, and for generating energy (ATP) to support cell growth and maintenance.

The main purpose of Metstoich is to link metabolic flux distribution among pathways with practical engineering parameters encountered in a standard biochemical engineering course, such as biomass yield (Y_{XS}), product yield (Y_{PS}), ATP yield ($Y_{X/ATP}$), etc. Pathway reactions are predefined and based on a specific yeast. Such an approach could also help to identify flux distribution among branch points.

There are several important inputs necessary for Metstoich to determine the flux map:

1) *Cell macromolecular composition;*
2) *Glucose distribution (usage) in central metabolic pathways for energy generation process;*
3) *P/O ratio;*
4) *ATP utilization efficiency (or simply called as ATP efficiency, η), the percentage of total ATP generated that is directly consumed in biosynthetic reactions;*
5) *Biomass yield, Y_{XS};*
6) *ATP yield, $Y_{X/ATP}$.*

There are four problem types that can be solved by Metstoich with above inputs:

a) *Calculation based on theoretical yield; or*
b) *Calculation based on experimental biomass yield, Y_{XS}; or*
c) *Calculation based on predefined ATP yield, $Y_{X/ATP}$; or*
d) *Calculation based on experimental biomass yield, Y_{XS}, and predefined ATP yield, $Y_{X/ATP}$.*

Table 1 summarizes a matrix of problem types, inputs, and outputs, and Figure 2 shows part of the input interface.

Users can specify: the cell composition (Figure 2); carbon source and electron donor if CO_2 is the carbon source (Figure 3); electron

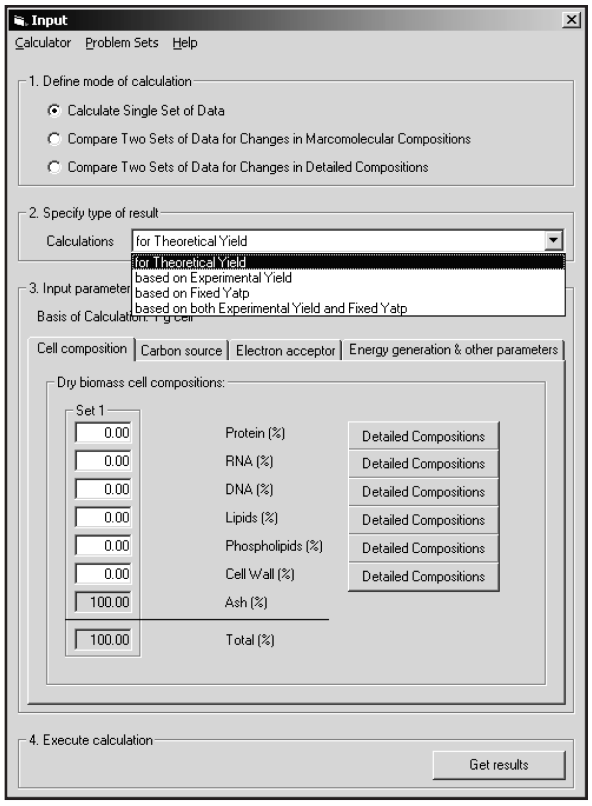


Figure 2. *Part of Metstoich input interface—basic information and cell compositions.*

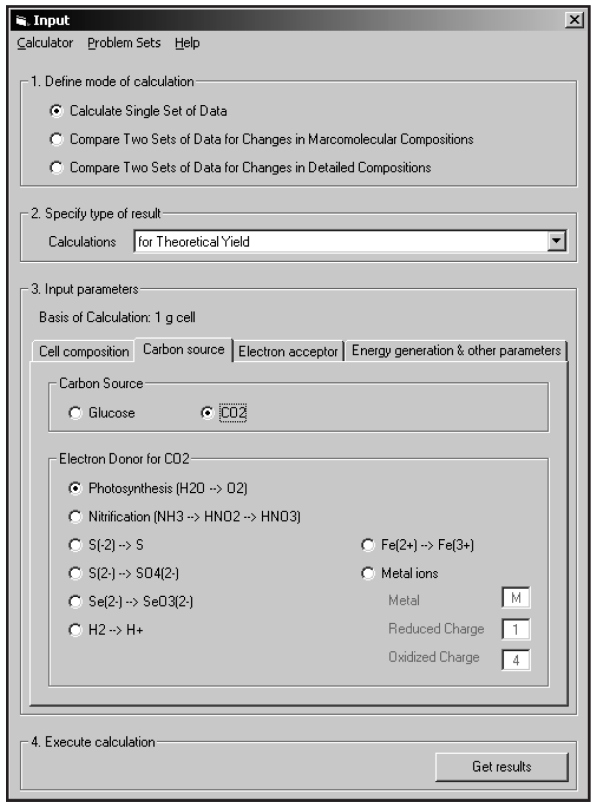
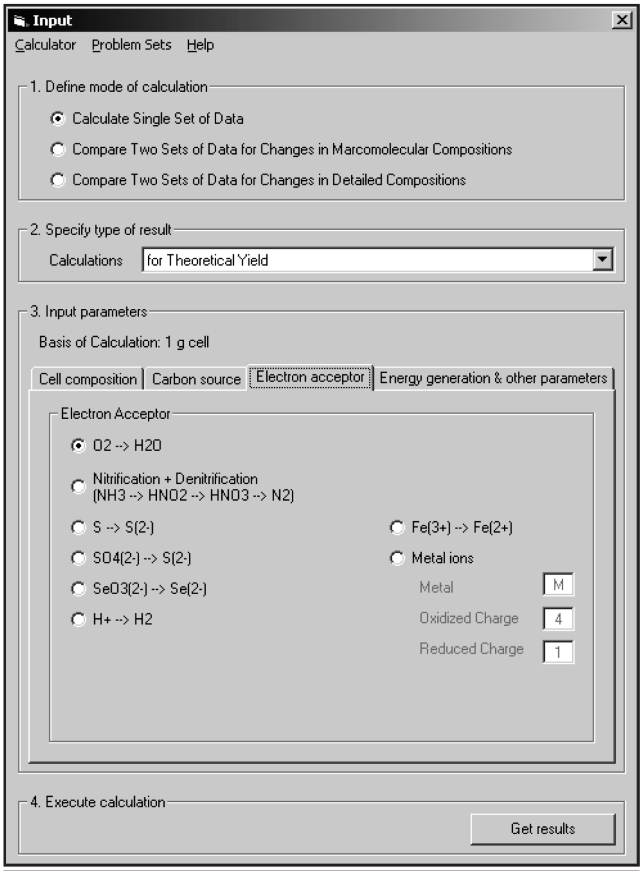
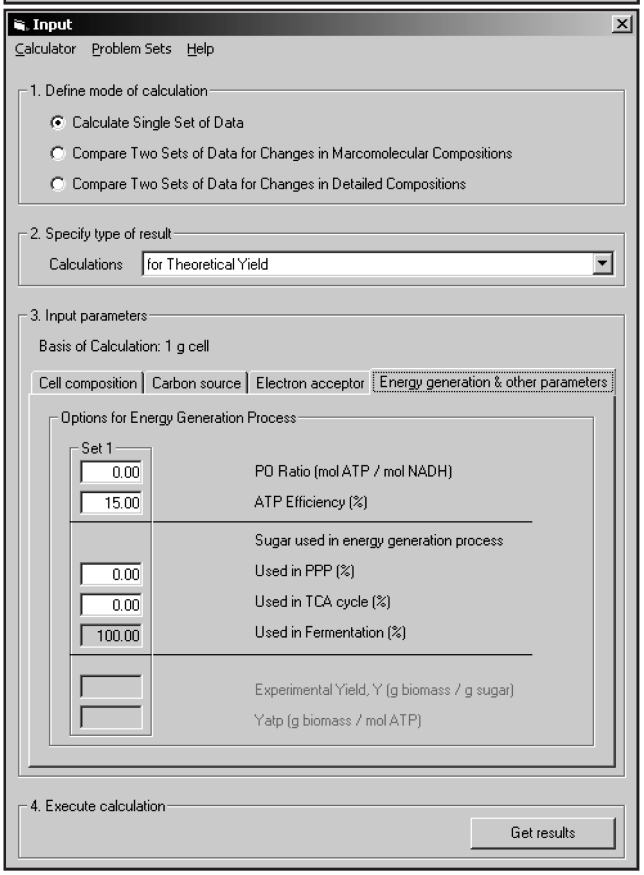


Figure 3. *Part of Metstoich input interface—carbon source.*





acceptor (Figure 4); and energetic issues of the microorganism (Figure 5). Metstoich can compare two sets of metabolic flux maps (Figure 6) and highlights fluxes with a defined degree of difference in percentage.

The results generated by Metstoich are organized into several levels of detailed worksheets with biochemical detail and illustrative reaction pathways included to make it more understandable. Levels of organized results are:

Cell Yield and Energetics *(Figure 7) – This worksheet is the executive summary of the overall performance of the cell with the inputted common engineering parameters;*

Fate of Glucose *(Figure 8) – This worksheet summarizes how much glucose is used for specified purposes via specified pathways;*

Figure 4. (top left) *Part of Metstoich input interface —electron acceptors.*

Figure 5. (bottom left) *Part of Metstoich input interface —energetic and other parameters.*

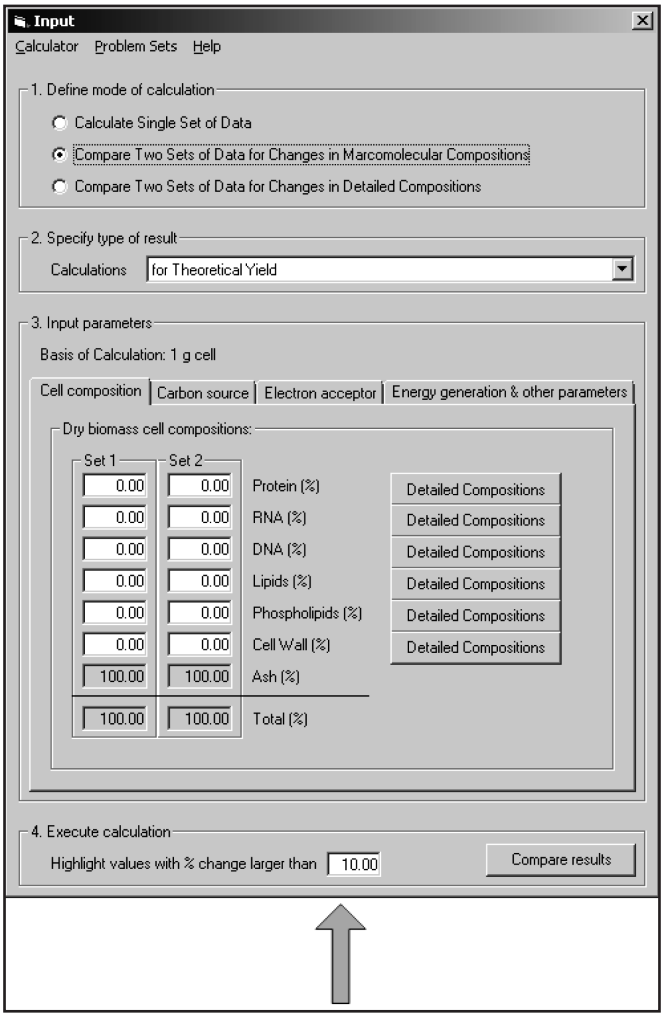


Figure 6. (above) *User can specify highlight values that changed larger than the given percentage.*

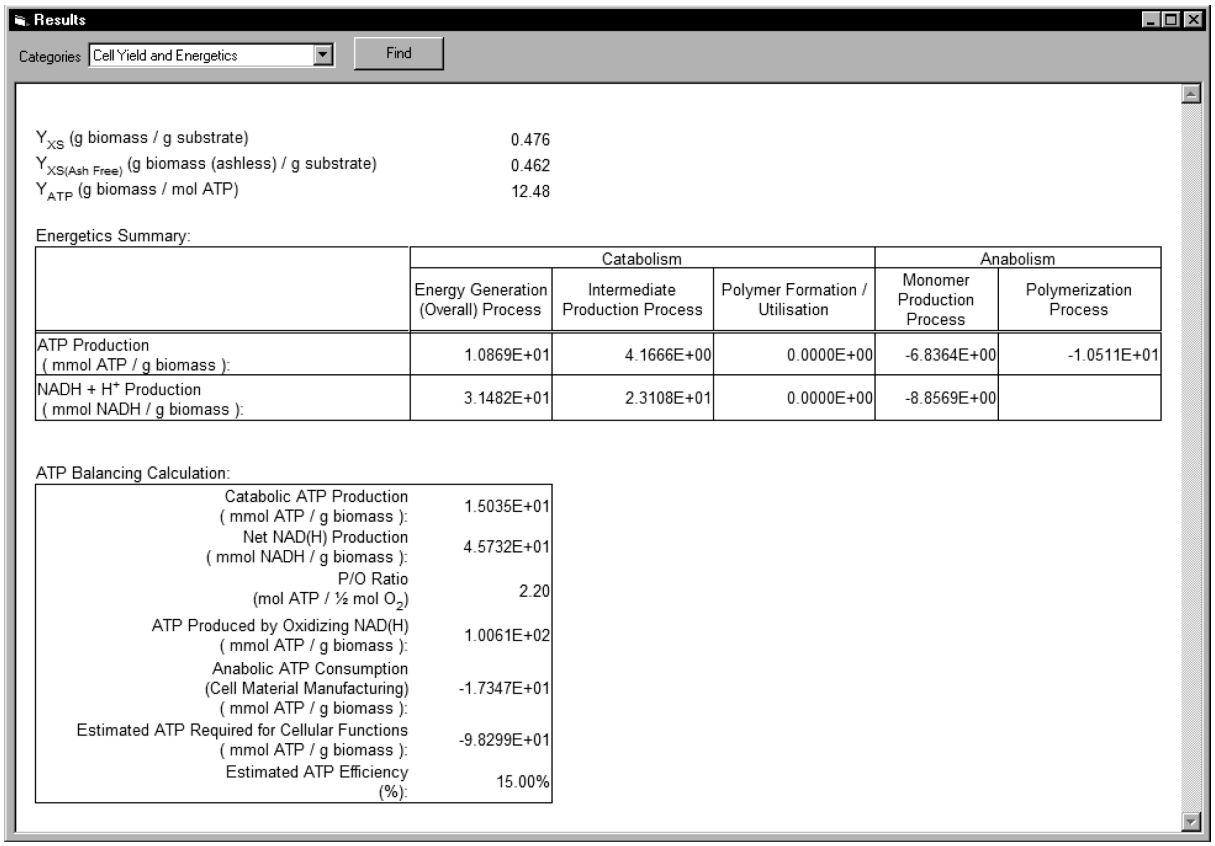


Figure 7. *"Cell Yield and Energetics," the cell yield (either estimated or given), $Y_{X/ATP}$, amount of ATP generated directly from reactions or oxidative phosphorylation are summarized.*

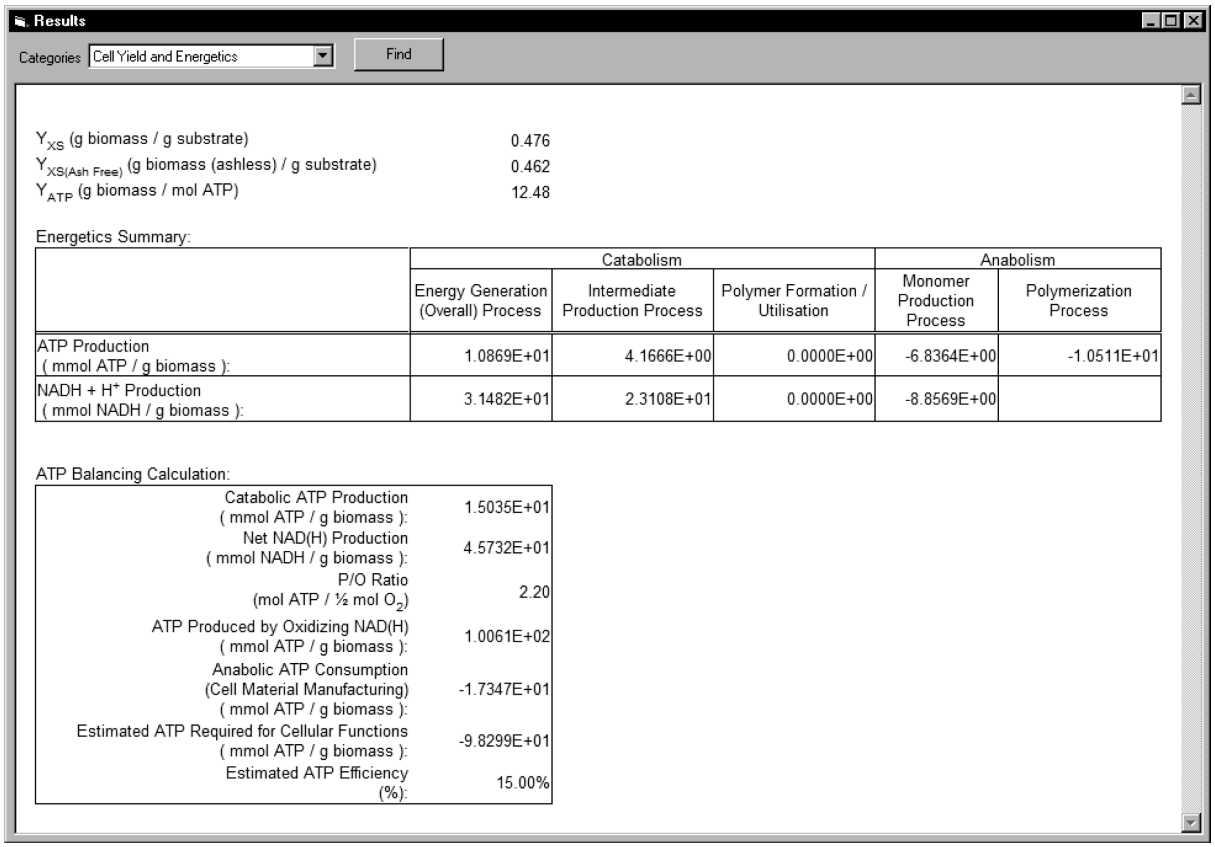


Figure 8. *"Fate of Glucose," glucose directly linked with biosynthesis or energy generation process is analyzed.*

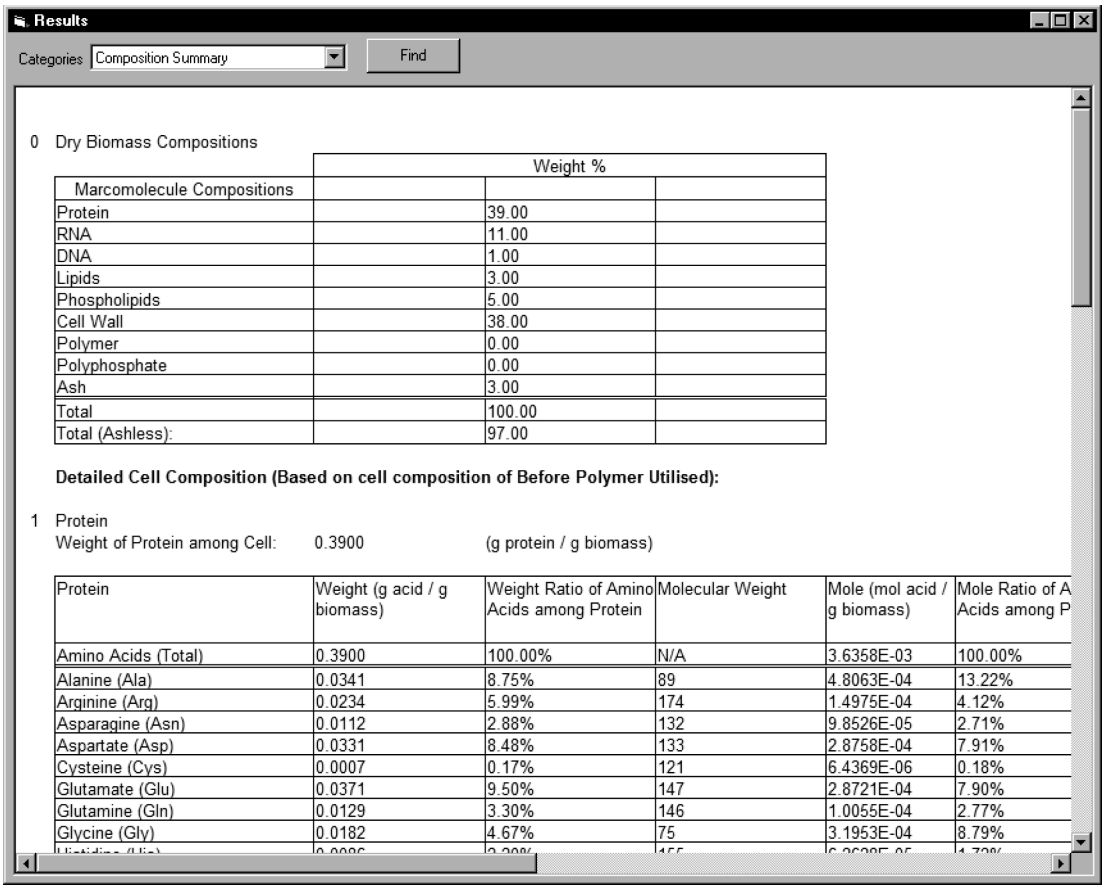


Figure 9. *All detailed biomass compositions, such as amino acid, etc., are summarized in "composition summary."*

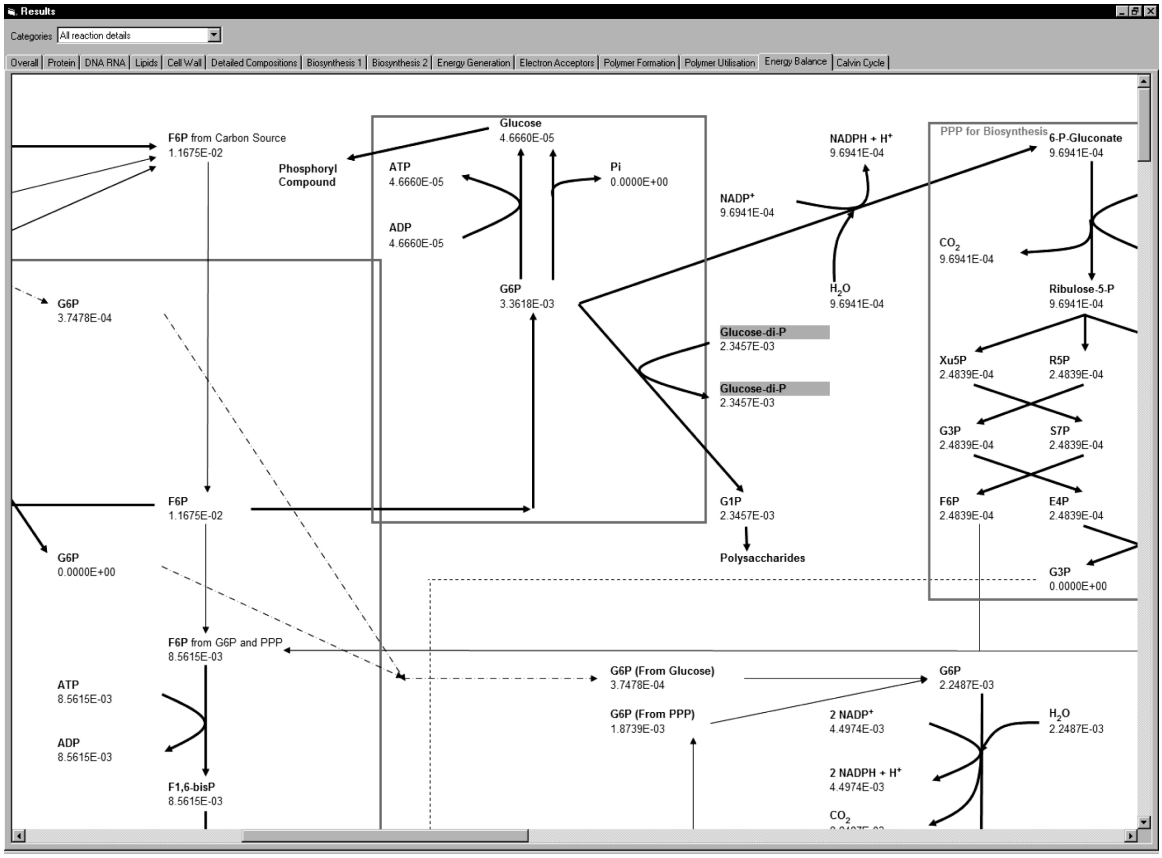


Figure 10. *"All Detailed Reactions" shows all biochemical reactions.*

Composition Summary *(Figure 9) — This worksheet summarizes cell compositions and their detail; and*

All Detailed Reactions *(Figure 10) – This worksheet shows the detailed flux maps for biosynthetic pathways—central metabolic pathways used for either biosynthesis purpose or energy generation purposes.*

Metstoich already contains amino acid production pathways and it is capable of analyzing amino acid production. Since Metstoich already contains information on major catabolic and anabolic pathways, it is easy to further include more production formation pathways such as antibodies, biofuel, etc.

Metstoich is focused on the static metabolic flux analysis, and therefore enzyme concentrations, kinetic expressions, intermediate concentrations, and thermodynamics have not been incorporated. An extension of Metstoich that incorporates thermodynamics and reaction kinetics, etc., has been developed and reported.[26-28]

The core calculation module of Metstoich is written using Microsoft Excel 2002 with VBA Macro. This core Excel module is responsible for constructing and displaying the metabolic flux map. The front-end graphical user interface was written in Visual Basic. Metstoich runs on Microsoft Windows 98, 2000, XP, and Vista with Microsoft Office 2000, XP, or 2003 installed.

Example to Demonstrate the Teaching of Quantitative Metabolism to Students

This is an example problem that students undertake as an exercise. It is taken from a number of problems included in the Metstoich package:

> The biomass composition (weight %) of a given yeast is as follows:
>
> Protein = 39%, DNA = 1%, RNA = 11%, Lipids = 3%, Phospholipids = 5%, Cell Wall = 38%, and Ash = 3%
>
> For energy generation, 10% glucose is used by pentose phosphate pathway, 60% glucose is used by the TCA cycle and 30% glucose is used by the fermentation pathway. The reported biomass yield is 0.4 g-biomass / g-glucose and let P/O ratio be 2.2 mol-ATP / mol-NADH. What is the corresponding $Y_{X/ATP}$ and ATP efficiency. What is the relationship between P/O ratio and $Y_{X/ATP}$?

Since Y_{XS} with P/O ratio are given, the "Experimental Y_{XS}" calculation mode should be used. With given input values, Metstoich returns $Y_{X/ATP}$ = 7.85 g-biomass / mol-ATP and ATP efficiency is 10.6%. And the relationship between $Y_{X/ATP}$ and P/O ratio is shown in Figure 11 at various P/O ratios:

With fixed Y_{XS} and cell compositions, glucose directly consumed to form biomass is always fixed at 1.43 g-glucose / g-biomass. The total glucose consumed is 2.5 g-glucose / g-biomass for the given Y_{XS} = 0.4. Therefore glucose consumed to generate energy is always 1.07 g-glucose / g-biomass, and it always generates 17.3 mmol-ATP and 50.1 mmol-NADH per 1.07 g-glucose consumed in assigned pathways. Therefore, total ATP generated in energy generation process = (17.3 +

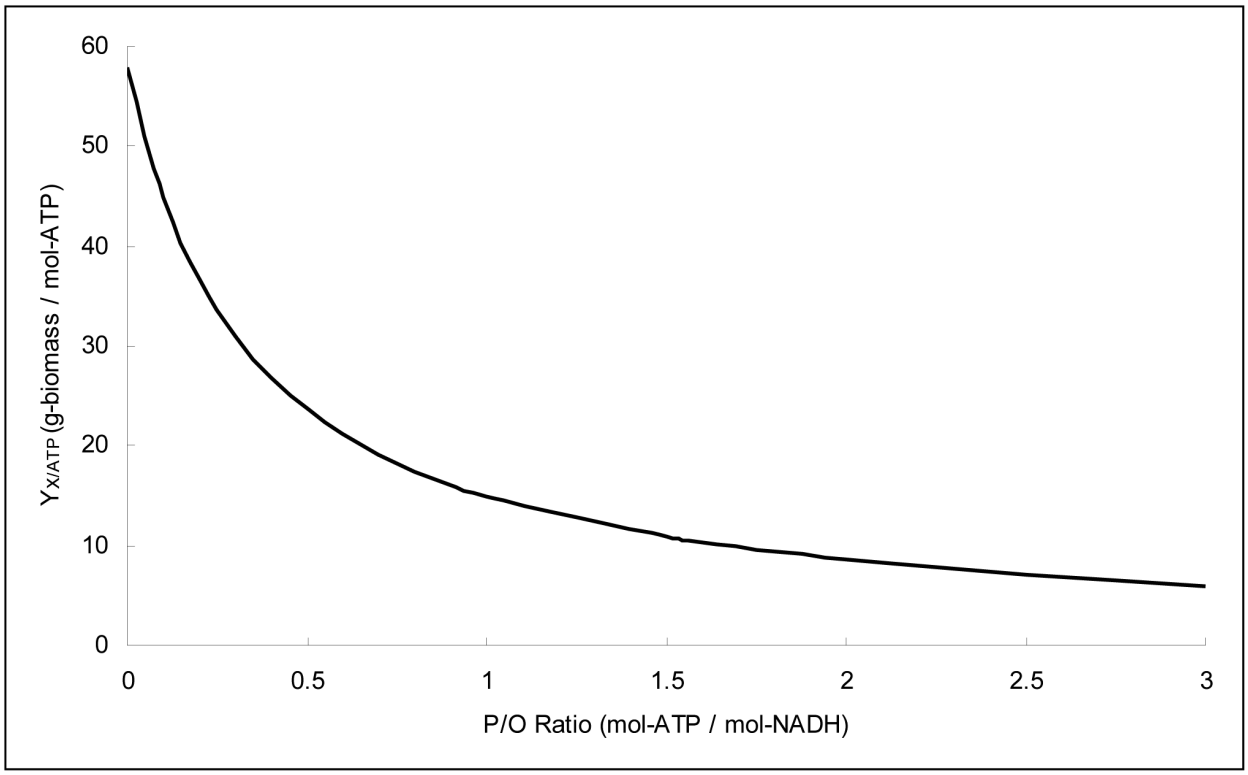


Figure 11. *Relationship between $Y_{X/ATP}$ and P/O ratio.*

P/O x 50.1 mmol-ATP) / 1.07 g-glucose. And $Y_{X/ATP}$ = 1 g-biomass / total ATP generated in energy generation process. It is suggested that normal $Y_{X/ATP}$ is around 10.5 g-biomass / mol-ATP. Using the "Experimental Y_{XS} and Fixed $Y_{X/ATP}$" calculation mode, it is found that the P/O ratio = 1.56 mol-ATP / mol-NADH and ATP efficiency = 14.27%.

Based on the fluxes given by Metstoich, students can draw simplified flux map as illustrated in Figure 12, Figure 13, and Figure 14 to understand the quantitative use of glucose by the cell and how much energy had been generated. By combining Figure 13 and Figure 14, students can generate an overall quantitative flux distribution for the given biomass.

COMMENTS ON METSTOICH

Professional evaluation was undertaken by Learnet of Hong Kong University. Metstoich had been reviewed by four leading academics in biochemical engineering from the U.K., the United States, Australia, and Singapore: Prof. D. Bogle from University College London, Prof. L. Nielsen from University of Queensland, Prof. D. Trau from National University of Singapore, and Prof. P. Fu from the University of Hawaii at Manoa. It was considered an excellent tool for learning of major biochemical engineering concepts such as $Y_{X/ATP}$, yield, etc. The feature that compared two sets of metabolic flux maps with a percentage change larger than a specified number was also highly regarded (Figure 6). In general, Metstoich has been rated as four stars out of five by these academics for different aspects such as interface design, quality of content, and learning potential.

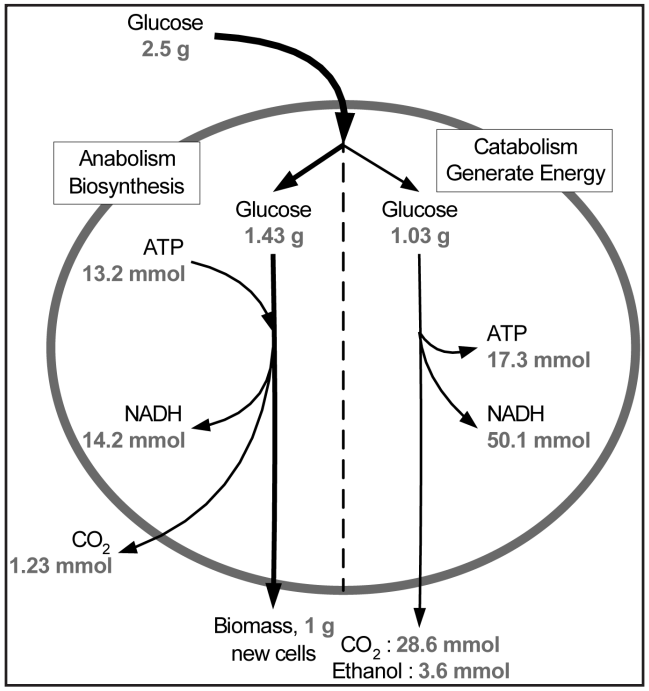


Figure 12. *Glucose used for biosynthesis and energy generation purposes, drawn based on Metstoich results.*

METSTOICH AS TEACHING TOOL

Metstoich has been applied in biochemical engineering and biochemistry classes at HKUST and it has been rated as easy to use by students. Students have been interviewed by the Center of Enhanced Learning & Teaching (CELT) of the Hong Kong University of Science and Technology (HKUST). It is agreed that Metstoich is easy to use, since the help functions and labels and buttons of the software are clear. The advantage of Metstoich is it can compare two sets of calculated results by highlighting the difference. Students felt that Metstoich contained too much information, however, since it covers from networks of reactions to energetics and cell yield, etc.

CONCLUSION

Engineering students are accustomed to quantitative concepts from their foundation courses. Biochemistry can also be taught quantitatively and when this is done, engineering students can appreciate the importance of metabolism in understanding and optimizing bioprocesses. Metstoich, a metabolic calculator for teaching purposes, was developed to introduce metabolism to students using quantitative principles. As such, it is useful to both engineering students and biochemistry/life sciences students, who normally do not have strong backgrounds or training in quantitative methods.

Metstoich has many novel features:

1. *Linking practical engineering parameters with cell growth, product yield, energetics, etc.;*
2. *Analyzing the flux though any reaction pathway;*
3. *Calculating how many nutrients are required for cell growth.*

Such analysis can provide useful information about how product yield is related with biomass yield, cell energetics, etc. Students can explore different metabolic options and are challenged to further explore their relationship to bioreactor/medium design.

The package has been well received by both academic experts in biochemical engineering and undergraduate chemical engineering and biochemistry students at HKUST.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support (Project : HKUST 00409E) of the Center For Enhanced Learning & Teaching (CELT) as well as their technical participation in the project.

REFERENCES

1. Nielsen, J., "Metabolic Engineering: Techniques for Analysis of Targets for Genetic Manipulations," *Biotech. Bioeng.*, **58**, 125-132 (1998)
2. Olsson, L., and J. Nielsen, "The Role of Metabolic Engineering in the Improvement of *Saccharomyces cerevisiae*: Utilization of Industrial Media," *Enzyme Microb. Technol.*, **26**, 785-792 (2002)
3. Stephanopoulos, G.N., A.A. Aristidou, and J. Nielsen, *Metabolic*

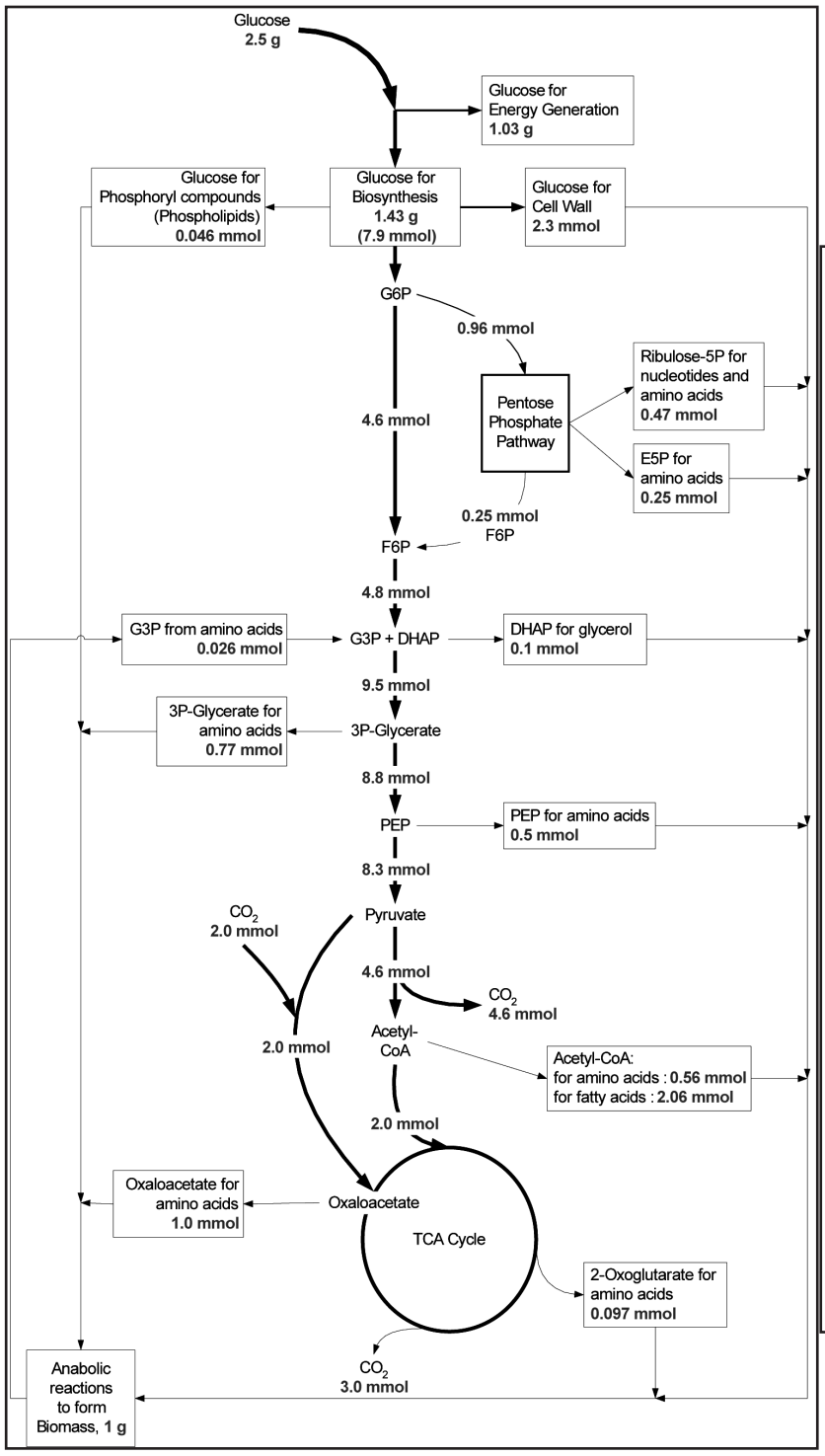
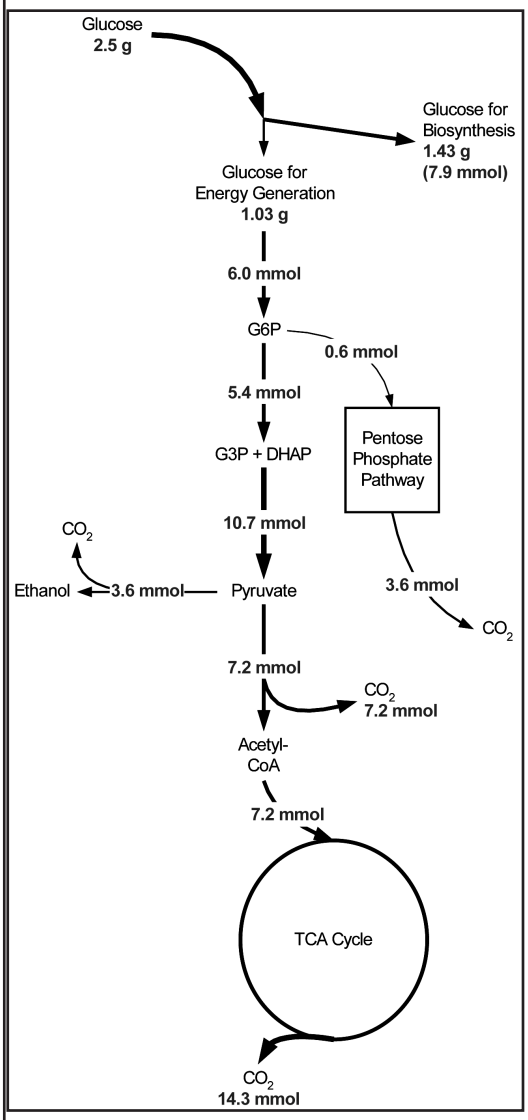


Figure 13. (left) *Fluxes among central metabolic pathways for biosynthesis, drawn based on Metstoich results.*

Figure 14. (below) *Fluxes among central metabolic pathways for energy generation purpose, drawn based on Metstoich results.*



Engineering, Principles, and Methodologies, Academic Press (1998)
4. Lee, S.Y., and E.T. Papoutsakis. Ed., *Metabolic Engineering,* Marcel Dekker, Inc. (1999)
5. Varma, A., and B.O. Palsson, "Metabolic Flux Balancing: Basic Concepts, Scientific and Practical Use," *Bio/technology*, **12**, 994-998 (1994)
6. Weichert, W., "Modeling and Simulation: Tools for Metabolic Engineering," *J. Biotech.*, **94**, 37-63 (2002)
7. Mendes, P., "Biochemistry by Numbers: Simulation of Biochemical Pathways with Gepasi 3," *Trends Biochem. Sci.*, **22**, 361-363 (1997)
8. Mendes, P., <http://www.gepasi.org/>
9. COPASI.org, <http://www.copasi.org/>
10. Sauro, H.M., "Scamp: A General-Purpose Simulator and Metabolic Control Analysis Program," *Comput. Appl. Biosci.*, **9**, 441-450 (1993)
11. Tomita, M., K. Hashimoto, K. Takahashi, T.S. Shimizu, Y. Matsuzaki, F. Muyoshi, K. Saito, S. Tanida, K. Yugi, J.C. Venter, and C.A. Hutchison III, "E-CELL: Software Environment for Whole-Cell Simulation," *Bioinformatics*, **15**, 72-84 (1999)
12. Ehlde, M., and G. Zacchi, "Mist: A User-friendly Metabolic Simulator," *Comp. App. Biosci. (CABIOS)*, **11**, 201-207 (1995)

13. Olivier, B., and J. Snoep, <http://jjj.biochem.sun.ac.za/> (2002-2003)
14. Barshop, B.A., R.F. Wrenn, and C. Frieden, "Analysis of Numerical Methods for Computer Simulation of Kinetic Processes: Development of KINSIM – A Flexible, Portable System," *Anal. Biochem.,* **130**, 134-145 (1983)
15. Dang, Q., and C. Frieden, "New PC Versions of the Kinetic-Simulation and Fitting Programs, KINSIM and FITSIM," *Trends Biochem. Sci.*, **22**, 317 (1997)
16. Klamt, S., J. Stelling, M. Ginkel, and E.D. Gilles, "FluxAnalyzer: Exploring Structure, Pathways, and Flux Distributions in Metabolic Networks on Interactive Flux Maps," *Bioinformatics*, **19**, 261-269 (2003)
17. Klamt, S., S. Schuster, and E.D. Gilles, "Calculability Analysis in Underdetermined Metabolic Networks Illustrated by a Model of the Central Metabolism in Purple Nonsulfur Bacteria," *Biotech. Bioeng.*, **77**, 734-751 (2002)
18. Neidhardt, F.C., J.L. Ingraham, and M. Schaechter, *Physiology of the Bacterial Cell – A Molecular Approach*, Sinauer Associates, (1990)
19. CellDesigner.org, <http://celldesigner.org/>
20. Cellerator.info, <http://www.cellerator.info/>
21. InNetics.com, <http://innetics.com/>
22. JigCell Project, <http://jigcell.biol.vt.edu/>
23. Wong, K.W., J.P. Barford, and J.F. Porter, "Understanding the Practical Consequences of Metabolic Interactions—A Software Package for Teaching and Research," *Computer Applications in Biotechnology,* 9th International Symposium, Nancy, France (2004)
24. Wong, K.W., J.P. Barford, and J.F. Porter, "Understanding the Practical Consequences of Metabolic Interactions—A Software Package for Teaching and Research," *Proceedings* of the Second Teaching & Learning Symposium, The Hong Kong University of Science & Technology, Hong Kong (2004)
25. Oura, E., "The Effect of Aeration on the Growth Energetics and Biochemical Composition of Baker's Yeast" with appendix: "Reactions Leading to the Formation of Yeast Cell Material from Glucose and Ethanol," Ph.D. Thesis, Helsinki University, Helsinki, Finland, (1972)
26. Sanderson, C.S., J.P. Barford, and G.W. Barton, "A Structured Dynamic Model for Animal Cell Culture Systems," *Biochem. Eng. Journal*, **3**, 203-211 (1999)
27. Sanderson, C.S., J.P. Barford, G.W. Barton, T.K. Wong, and S. Reid, "A Structured Dynamic Model for Animal Cell Culture Systems: Application to Baculovirus / Insect Cell Systems," *Biochem. Eng. Journal*, **3**, 219-229 (1999)
28. Sanderson, C.S., J.D. Jang, J.P. Barford, and G.W. Barton, "A Structured Dynamic Model for Animal Cell Culture Systems: Application to Murine Hybridoma," *Biochem. Eng. Journal*, **3**, 213-218 (1999) ❐

THE MICROBIAL FUEL CELL AS AN EDUCATION TOOL

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According to Accreditation Board for Engineering and Technology (ABET) outcome 3d, graduates from engineering programs must have the ability to function on multidisciplinary teams.[1] Unfortunately, evaluation shows that engineering students are not well positioned to understand new concepts from a variety of disciplines and integrate them into what they learn in their own disciplines.[2] This is especially true for concepts in emerging areas, such as life sciences. Obviously the emergence of technological breakthroughs in new arenas is stimulating faculty members to include related multidisciplinary concepts in their course designs so that students can be prepared to meet the industrial challenges presented in applying new technologies within industrial settings.[1]

Motivated by the lack of appropriate tools that can be used to teach chemical engineering undergraduate students, especially to teach them how to integrate life sciences and engineering concepts, we have developed the microbial fuel cell education module (MFCEM), a hands-on learning module that can be used for learning multidisciplinary concepts in an active group-learning modality. This module uses the principles of mass and energy conversions applied in a microbial fuel cell (MFC) to integrate various concepts taught in biology, chemistry, electrochemistry, and engineering. In this paper, our goal is to show how the MFCEM can be used as an aid in teaching a senior-level course in chemical engineering—Introduction to Bioprocess Engineering (ChE 475). Figure 1 shows the components of the module and how we implemented it in the classroom.

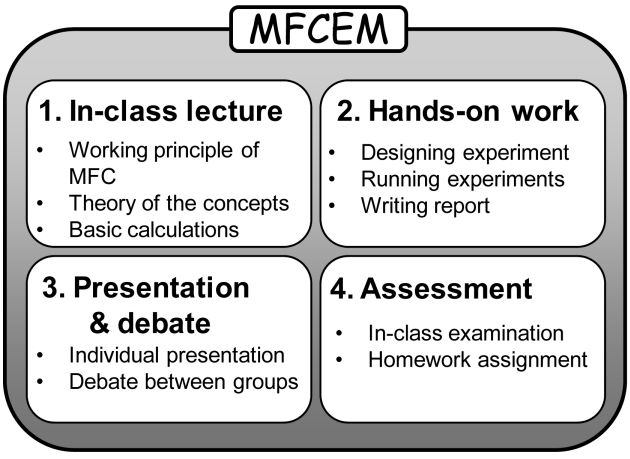

Figure 1. *Methodology for implementing the microbial fuel cell education module.*

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MICROBIAL FUEL CELL EDUCATION MODULE

Class lectures were used to introduce the theory of various processes important to understanding microbial respiration, the thermodynamic and kinetic principles of the processes involved in energy conversion in MFCs, and the basic calculations used in electrical engineering (*e.g.*, current and power). The hands-on work consisted of the operation of an MFC in the laboratory. For the laboratory exercises, we prepared a manual to instruct the students about safety issues; equipment needed to run the MFC, with photographs; step-by-step procedures, also with photographs; sample experimental results; sample calculations; and final-report requirements. The students, assembled into two groups, ran the MFC, computed the energy conversion, and presented the results to their classmates. Debates, moderated by the instructor, on the results obtained by the various groups, were aimed at reinforcing the concepts discussed in the lectures. Last, we assigned a set of problems to test understanding of the concepts and to evaluate the role of the hands-on active experience in the classroom.

TABLE 1
The Concepts, Related Topics, and Mathematical Expressions Introduced Using the MFCEM

Concepts	Specific topics	Mathematical expression*	Reference
Cellular respiration Microbial growth kinetics	• Metabolic pathway • Electron transport chain • Redox reactions in respiration • Microbe-solid interactions • Monod kinetics	$\frac{dX}{dt} = \mu_{max} X \frac{S}{K_S + S}$ $\frac{dS}{dt} = -\frac{\mu_{max} X}{Y_{X/S}} \frac{S}{K_S + S}$	[6,9]
Electrode potential (Electrochemical equilibrium)	• Nernst equation	$E_A = E_M^o + \frac{0.059}{2} \log \frac{(M)_{ox}}{(M)_{red}}$ $E_C = E_{O_2}^o + \frac{0.059}{4} \log \left[\frac{1}{p_{O_2} \cdot [H^+]^4} \right]$	[6,7,10]
Overpotential (Electrode kinetics)	• Butler-Volmer equation • Electrode polarization	$i = i_0 \left[\exp\left(+\frac{0.5\eta F}{RT} \right) - \exp\left(-\frac{0.5\eta F}{RT} \right) \right]$	[6,10]
Current	• Faraday constant • Calculation of current from material balance and growth kinetics in MFC	Faraday constant = electrical charge of an electron × Avogadro constant $I = \frac{V}{R_{ext}}$	[7]
Power	• Differences between current & power and energy & power	$P = V \cdot I = \frac{V^2}{R_{ext}} = I^2 \cdot R_{ext}$	[7]
Charge conservation	• Faradic efficiency	$\varepsilon_c = \frac{\int_0^t I \, dt}{F \, n \, \frac{\Delta S}{M}}$	[7,11]
Energy conservation	• Energy efficiency • Material and energy balance for MFC	$\varepsilon_E = \frac{\int_0^t V \cdot I \, dt}{\Delta H_c . m_{in}} = \frac{\int_0^t I^2 \cdot R_{ext} \, dt}{\Delta H_c . m_{in}}$	[7]
Sustainability	• Definition of sustainability • Sustainability of power generation in MFCs	–	[12,13]

* Details on the development of these equations, and example calculations using experimental data, were included in the MFCEM handout given to the students.

The incorporation of the MFCEM into the bioprocess engineering course, ChE 475, gave us an opportunity to teach the concepts through an active-learning process. Compared to standard lecture-based, passive learning, the hands-on active-learning process helps students to visualize and more fully think through what they learn and helps them to make connections between concepts that they learned before.[3] As claimed in the well-known learning retention pyramid,[4] students remember concepts best when they see a demonstration (50%), engage in a debate or discussion (70%), or have a chance to do something real and apply their knowledge immediately (90%). With the MFCEM we particularly emphasized practice by running experiments that were an immediate application of the in-class lecture and having the students prepare reports, perform homework assignments, and hold in-class debates with the active involvement of the other students in the audience, who asked questions or expressed opinions on one side or the other of the debate. The remainder of the material in ChE 475 was taught in a passive manner, with the professor lecturing and the students taking notes and completing homework assignments based on their notes and reading. We expected that the introduction of the MFCEM into our course would significantly increase learning retention of the topics in ChE 475 and of the multidisciplinary concepts introduced by the MFCEM.

IN-CLASS LECTURE: THEORY

In the ChE 475 course, we used *Bioprocess Engineering*, written by Shuler and Kargi (2002).[5] After completion of the first six chapters students were familiar with the fundamentals needed to understand MFCs and we then introduced multidisciplinary concepts using the MFCEM. We do not discuss all the concepts in this paper because of space limitations; however, they were discussed in considerable detail in the classroom and in the MFCEM manual given to the students. While some of the concepts had been taught in previous courses, we reintroduced them so that students could connect the new concepts with previously learned concepts. The concepts, related topics, and mathematical expressions[6-8] that were introduced using MFCEM are summarized in Table 1.

The topics were presented by asking a series of questions and helping the students find the answers. The following paragraphs present selected questions we asked and give a brief discussion of how they were implemented.

How did the scientist who ran the first MFC think to use microbes? Our theory section started with this question and it was actively discussed in the classroom in a group format to give the main idea behind the MFC. Then we introduced the concept of how a single cell grows, duplicates, and gains energy. We showed a single cell (Figure 2A) and described the main idea behind MFCs, which is separating the oxidation and reduction reactions in the respiration system. After showing Figure 2A, we asked the students to build an MFC. The students worked to separate the two environments and make the MFC depicted in Figure 2B. This process helped them to understand the basic principle of the MFC, that of separating the oxidation and reduction reactions using a proton-exchange membrane (PEM) and connecting the two reaction environments through an external circuit. Later we discussed in detail and explained why we need to use a proton-exchange membrane (Figure 2B). This helped the students better understand what a cathode and an anode are. They learned that oxidation happens at the anode and reduction at the cathode.

How are the electrons transferred from bacteria to the solid electrode? The interaction of microbes with solid materials is a fascinating new topic, not only in MFC research but also in microbiology and environmental science. Electron transfer mechanisms were introduced and the students were taught why electrons cannot jump directly from microbes to solid surfaces, *i.e.*, that electrons must be transferred by a redox reaction via: 1) a mediator, a chemical that accepts electrons resulting from the microbial respiration process and transfers them to the solid electrode, or perhaps 2) linkage of the microorganisms with the electrode surface by nanowires or cytochromes. The students were excited about these topics, which constitute cutting-edge research questions in microbiology.

What are the source of and the sink for the electrons? This question was answered by revisiting the major metabolic pathway concepts, taught earlier in the course. We showed how electrons are derived from the microbial respiration system and transported to an electron acceptor (in this case a solid electrode) through the electron transport chain. This used to be a mundane subject for the students, but now there was a

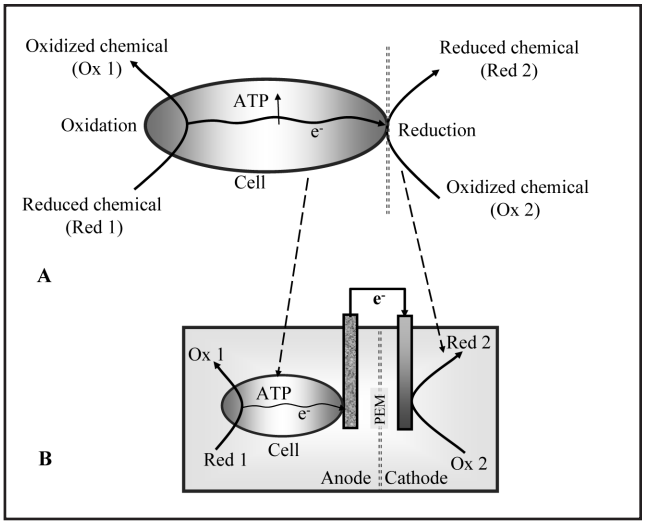


Figure 2. *The original idea of a microbial fuel cell described using a single cell. (A) The redox reactions—oxidation and reduction—in the microbial energy generation process. (B) The separation of the oxidation and reduction reactions, using a proton exchange membrane, to build a microbial fuel cell.*

real-life application for the metabolic pathways and therefore they appeared to be engaged in the subject as evidenced by the energy demonstrated by students when they expressed their ideas and the content of their group discussions. To further facilitate discussions, the idea of using two different types of bacteria was introduced—one using lactate and the other using glucose as the electron donor.

What do we mean by the electrode potential, current, energy, and power of a fuel cell? The electrode potentials are thermodynamic properties and are calculated using the Nernst equation (Table 1). When current is passed through the electrode, however, the thermodynamic equilibrium does not exist anymore; rather the current needs to be calculated using the Butler-Volmer equation describing electron transfer kinetics. As a result of this discussion, the students improved their understanding of the differences between equilibrium and non-equilibrium processes. The concept of overpotential is vital to understanding batteries, fuel cells, corrosion processes, and electrochemical sensors. Using the MFCEM, students were introduced to the concepts of polarization curves (cell potential vs. current) and overpotential. In addition, they learned basic electrical engineering concepts such as electrical potential, current, power, and energy, and how to perform measurements for and calculations of their values in MFCs.

How much electrical charge or how many electrons can we derive from microbial reactions? This question was asked to introduce the concept of Faradic efficiency. The students learned how to calculate the maximum possible number of electrons transferred as a result of the differences in oxidation states of chemicals and the concentrations of chemicals in the growth medium. Students had to do material balances to calculate Faradic efficiency. Discussions resulting from this question helped to introduce the concept of charge conservation in electrochemical systems and the Faraday constant (Table 1).

How much power can be harvested from an MFC for a given amount of substrate? The calculation of power from current and potential helped students to understand simple electrical engineering concepts and taught them the differences between potential and current, and between power and energy. These concepts often confuse students in the electrical circuit course required during their undergraduate studies. Thus, the MFCEM allowed them to integrate electrical engineering concepts with chemical and biochemical engineering concepts.

How sustainable is power generation in an MFC? Students are often exposed to general terms, such as the sustainable development of the economy of a country, and they need to extend the application of the term "sustainable" to power generation in MFCs. Sustainability of power generation in MFCs is defined as the ability to generate power at a constant rate over long periods, and it is evaluated by monitoring the energy production and consumption using different loads on the MFC. There is no general criterion by which one cell produces power in a sustainable manner and another does not: it all depends on the ratio of the power generated to the power consumed. When the rate of energy consumption is higher than the rate of energy generation by the microorganisms, the MFC does not produce power in a sustainable manner. The opposite is true as well, however, the MFC produces power in a sustainable manner when the rate of energy consumption is lower or equal to the rate of energy generation by the microorganism.[14]

HANDS-ON WORK: EXPERIMENTS

We had nine students run the experiment (selection of students was on a volunteer basis), and the group of experimenters was divided among two teams, each of which was assigned one of two options. One team ran the MFC experiments using *Shewanella oneidensis* while the other used *Klebsiella pneumoniae*. The goal of using two different microorganisms was to observe the difference in power generation and later to arrange a debate on the role of the different respiration systems in accounting for that difference. During the experiment each team tested the effects of the selected variable (microorganisms, see Table 2). To implement the pedagogy in crowded classes, multiple groups could be used and each group could be subdivided into smaller teams: each team would investigate one of the variables listed in Table 2 and report their findings back to their other group members. This paper describes our classroom experience, in which only one group consisting of two teams worked on understanding the roles of different microorganisms in MFCs. The remaining 14 students received information via lecture, from listening to debate presentations by the two groups, and from participation during and after the debate through asking questions and expressing their own opinions.

TABLE 2
Experimental Conditions, Variables Tested, and Topics for the Debate

Variable (for groups)	Conditions in the MFCs (for teams)	Topics for debates between teams
Microorganisms	1. *Shewanella oneidensis* 2. *Klebsiella pneumoniae*	Cellular respiration
Electrode material	1. Graphite 2. Stainless steel	Microbe-solids interaction
Substrate	1. Glucose 2. Natural biomass	Renewable energy source
Load	1. Low resistor 2. High resistor	Sustainability

At the end of the experiments, the teams prepared reports and gave class presentations. The presentations had the format of a debate. The two teams, which had used different microorganisms, compared their

power generation. Debates centered around why one of the microorganisms produced more power than the other, and a team's position had to be substantiated using the calculations shown in the theory section. We noticed significant involvement of the students, interesting questions, and many recommendations on how to increase the power generation in such devices.

Construction of the MFC. To run the experiments, students used a two-compartment MFC. The components of the MFC and the steps required to construct it are shown in Figure 3. The compartments were made of polycarbonate (8 cm × 8 cm × 3.7 cm) and were furnished with openings at the top to make electrical connections with the electrodes. Cation exchange membrane (ESC-7000, Electrolytica Corporation) was used to separate the compartments. The cover plates were made of polycarbonate and had three openings for inlet and outlet tubing connections. To prevent leakage, rubber gaskets were used between compartments and between the compartments and cover plates. Screws with wing nuts were used to hold the reactor together. Silicone rubber tubes were used to deliver liquids and gases and to remove them from the respective compartments. The electrodes were made of graphite plates (GraphiteStore.com, Inc.) with surface areas of 23 cm^2 for the anode and 63.4 cm^2 for the cathode. These were placed against the cation exchange membrane, parallel to each other.

To construct the MFC, students followed the steps shown in Figure 3. The steps are: 1) inserting the electrodes into the compartments, 2) placing a gasket on the inner side of each compartment, 3) placing the cation exchange membrane over the first gasket, 4) placing another gasket on the other side of the membrane, 5) putting the compartments together, 6) placing gaskets outside of the compartments, 7) placing the cover plates, 8) holding the compartments and cover plates together using wing nuts and bolts, and 9) connecting the tubing and then autoclaving the MFC. After autoclaving, the reactor was cooled down to room temperature and the anode and cathode compartments were filled with anolyte and catholyte, respectively. The anode was inoculated with the selected bacteria for each group. Then in step 10 students placed the reference electrode in the cathodic compartment and connected the electrical wire, resistor, etc. These step-by-step procedures are described in a written manual, and it is available upon request from the authors.

ASSIGNMENTS

The assignments were designed to evaluate understanding of the multidisciplinary concepts taught using the MFCEM. In constructing assignment questions we considered the different levels in Bloom's taxonomy[15] and the levels of learner knowledge described by Apple and Krumsieg(2001)[16] that are expected to be evident in responses generated by college graduates. We summarize the assignment problems in Table 3 (next page), and match the assignments with levels in Bloom's taxonomy and with Apple and Krumsieg's levels of learner knowledge. The questions are discussed in the following sections; however, because of space limitations we give only selected answers here. The full range of answers is available upon request.

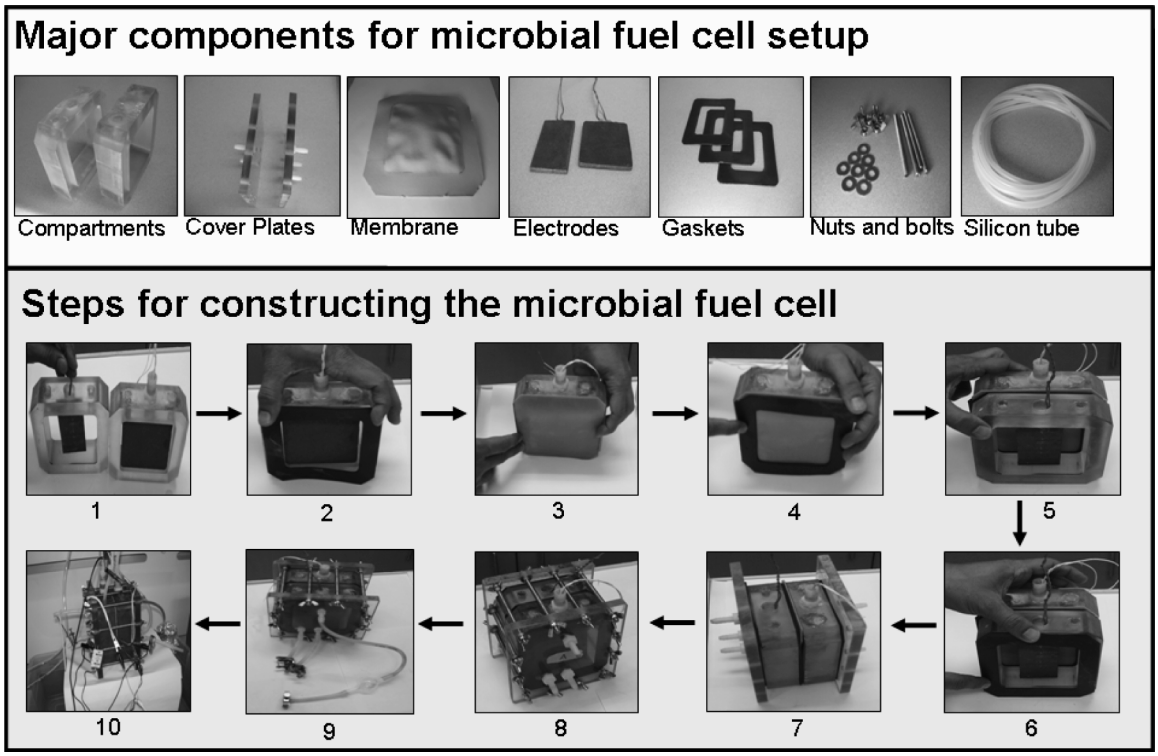


Figure 3. *Major components used and steps followed to construct the microbial fuel cell used by the students.*

The first problem was designed to determine whether the students understood the principles of the process and could perform basic calculations quantifying processes in MFCs, electrochemistry, and electrical circuitry. Solving this problem required use of Bloom's levels of knowledge, comprehension, application, and evaluation, and Apple and Krumsieg's corresponding levels of learner knowledge, as shown in Table 3. In Problem 1a, the students described the basic idea of MFCs using their knowledge of microbial respiration and the electron transport mechanisms. In part 1b, they used the concepts of material balance and charge balance to calculate current, power, current density, and power density. In part 1c, the students used their conceptual understanding of electrical circuits and material balances to calculate the amount of glucose required to produce sufficient energy to power a light bulb for one hour. In part 1d, they were asked to think creatively and apply learned concepts to MFCs. This problem also tested the students' ability to integrate concepts from electrical engineering with those from chemical engineering and apply them to scaling up a device. In part 1e the students were asked to discuss the future of MFCs and evaluate their potential for providing an alternative energy source.

The second problem was designed to relate concepts surrounding cell-growth kinetics in bioreactors with those relevant to MFCs, both of which are taught in this course. This problem was designed to include the analysis and synthesis, and evaluation levels of Bloom's taxonomy, and the corresponding working expertise and research levels of Apple and Krumsieg's taxonomy. In part 2a, students were asked to develop a mathematical model to quantify variations in substrate concentration and power generation over time and to construct the plots shown in Figure 4A and 4B. This part was designed to determine whether students could integrate the idea of the Faraday constant with mass and energy conservations laws, which are taught in physical chemistry/electrochemistry and basic chemical engineering courses. Constructing the plots in Figure 4 required the solving of simultaneous first-order differential equations, using concepts taught in our sophomore-level numerical methods course. Part 2b required the calculation of power generation using different values for microbial growth kinetic parameters and columbic efficiency. Figure 4C shows how power generation and the time to reach the maximum power depend on the Monod kinetic constant (Ks). The students needed to draw plots similar to that in Figure 4C to evaluate the effects of the maximum growth rate and the columbic efficiency. This part of the problem was designed to evaluate the students' abilities to interpret the physical meaning of the growth kinetic parameters in the context of the MFC. In part 2c, the students discussed how the columbic efficiency would change if an external electron acceptor (oxygen) were present in the anodic compartment. This question was asked to assess their understanding of how electron transport is involved in the microbial respiration system. Part 2d was open-ended and matches with Bloom's levels V and VI, synthesis and evaluation, respectively, and Apple and Krumsieg's Level V, research. In this part students were able to assess the variation in power generation as a function of actual process variables including temperature, pH, and conductivity.

ASSESSMENT OF THE MFCEM

The assignments (Box 1, pg. 164) could be completed if the students could successfully integrate multidisciplinary concepts. For example, to construct a model equation (Problem 2a) for the substrate concentration, current and power generation in a batch MFC, students needed to integrate the concepts of microbial growth kinetics, mass and charge conservation, and Faradic efficiency.

The effectiveness of the MFCEM was assessed by: 1) comparison of the results of the assignments completed by the students who had run hands-on experiments with those of students who had not; 2) our observations during the experimental activity and the debate; and 3) the students' comments. Since the students running the experiment had volunteered we expected them to be more curious, take more initiative and be self-motivated, and therefore to be better prepared to learn the MFC concepts. We indeed found this to be true, as they earned 42% more points on average than the students who did not run the experiments. The result was shown to be statistically significant using a 95% confidence level ($\alpha = 0.05$) and the null hypothesis that the two averages were different. In a two-tailed t-test with 18 degrees of freedom the p value was 0.019 ($<\alpha$). Also, there were several interesting observations made during the debate between the two teams doing the experiments:

1) *The students discussed aspects of microbial respiration and the electron transport processes, including concepts for which scientists are still trying to find answers;*

2) *Current and power calculations were vividly discussed, and one of the students even commented that "potential,*

TABLE 3
Levels in Bloom's Taxonomy and Apple and Krumsieg's Levels of Learner Knowledge Used in Constructing Questions to Evaluate Learner Performance in the MFCEM

Levels	Bloom's level[15]	Apple and Krumsieg's level of learner knowledge[16]	Problems assigned
I	Knowledge	Information	1b, 2a
II	Comprehension	Conceptual Understanding	1a, 1c
III	Application	Application	1d
IV, V	Analysis and Synthesis	Working expertise	2a, 2b, 2c, 2d
VI	Evaluation	Research	1e, 2d

current, energy, and power concepts finally made sense" to him; and

3) *Many students who previously were silent in class were effectively involved in the discussions.*

We are aware that our study is limited and a more detailed assessment of the effectiveness of this tool is needed. We expect to collect more data in the upcoming semesters. First, it will be important to come up with other performance measures besides homework assignments; we will likely include a critical-thinking rubric being developed in other companion work,[17] concept inventories that our group will develop based on similar strategies taken by Streveler, et al. (2008).[18] Also, it will be important to eliminate the possibility that only the more motivated students elect to participate in the active experimental aspect of the course and that such students are already inclined toward a more independent learning component. To safeguard against this we will organize student groups by random selection or based on a fairly equal distribution of GPAs between students within the active experimental groups and those exposed to passive lectures. We could also have a second experimental activity of equivalent rigor in which the student groups are switched: those that first did experimental activity and formed debate squads would only have the passive lecture for the second experiment, and vice versa. Finally, a detailed survey on student perspectives could be used in which the students themselves compare the learning environments, their growth in understanding, and their ability to work with other group members independent of instructor input.

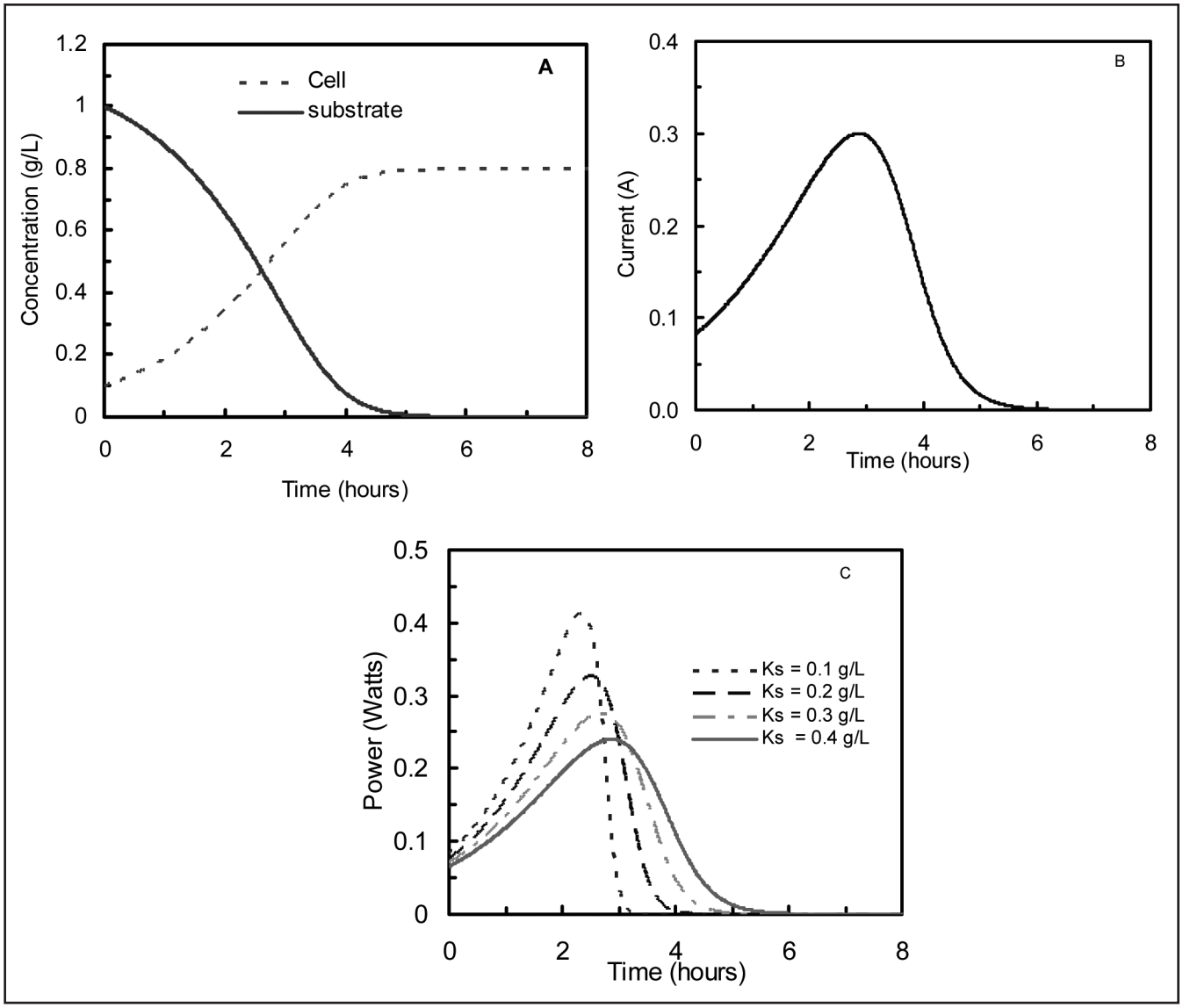
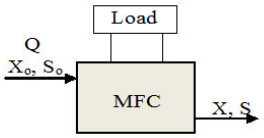


Figure 4. *(A) Microbial cell concentration and substrate concentration vs. time plotted using the model equation derived in Problem 2a. (B) Current vs. time calculated for Problem 2a. (C) Power generation vs. time calculated for various Monod constants (Ks). Similar figures were plotted by the students to show the effects of the maximum growth rates and columbic efficiencies.*

BOX 1: Problems assigned after introducing the MFCEM

Problem 1. In a continuous microbial fuel cell (MFC) the cells are grown in the planktonic phase, anaerobically, using glucose as the electron donor, and the electrons are transferred to the solid electrodes without any kinetic limitation.



Suppose the cell growth rate can be described by Monod kinetics as

$$r_x = \frac{0.9\,S \cdot X}{0.7 + S}$$

At a steady state, the sterile growth medium is fed at a rate of 1 L/h. The working volume of the anodic compartment of the MFC (the liquid volume) is 10 L. The inlet glucose concentration is 2 g/L and the cell yield coefficient ($Y_{x/s}$) is 0.5. Electrons are derived from the substrate according to the following reaction.

$$C_6H_{12}O_6 + 6H_2O \Rightarrow 6CO_2 + 24H^+ + 24e^-$$

a) Can you explain why and how the electrons are transferred from cells to the solid electrode?

b) Calculate how much current can be produced if the Faradic efficiency is 1.0 (all the derived electrons are transferred to the solid electrode). If the cell potential is maintained at 0.5 V, what will the power produced by the MFC be? What will the current density and power density be if the anode surface area is 5 m^2 and the Faradic efficiency is 1.0 at an average cell potential of 0.5 V?

c) How much glucose would be needed to power a 60-W light bulb for an hour, if the power generation were the same as that in part a?

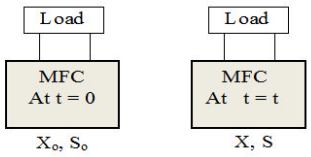
d) MFCs are an energy source characterized by low power generation. If the energy generation of the MFC remains the same as that calculated in part a, how would you scale up an MFC to harvest sufficient energy in two hours to power a laptop for one hour? Note that an Apple Mac laptop operates at 97 watts.

e) How feasible is it to design a MFC that will power a laptop directly? Can you predict the future for MFCs as an alternative energy source?

Problem 2. A laboratory-scale batch MFC is started with a cell concentration of 0.1 g/L in an anaerobic anode chamber with a volume of 0.25 L. The growth kinetic parameters are μ_{max}=0.9 hr^{-1} and K_s=0.4 g/L. The initial substrate (glucose) concentration is 1 g/L. The cell growth can be described using Monod kinetics, and the substrate consumption rate is

$$-\frac{dS}{dt} = \frac{\mu . X}{Y_{x/s}}$$

where μ is the specific growth rate, X is the cell concentration and the cell to substrate yield coefficient $Y_{x/s}$ is assumed to be equal to 0.7.



a) Construct a mathematical model to quantify the variation of substrate concentration, current, and power over time. How long will it take to consume 90% of the substrate? What will the concentration of cells be at that time? When will the MFC produce a maximum current? What would the maximum theoretical power be if the cell potential could be maintained at 0.8 V?

b) What would happen to the power generation if the Monod half rate constant (K_s), the maximum growth rate, and the Columbic efficiencies were different?

c) What inference can you make about the Faradic efficiency if the anode chamber is aerobic instead of anaerobic?

d) Qualitatively predict the variation of power generation with the variation of reactor temperature, pH, and conductivity.

CONCLUDING REMARKS

We successfully developed and implemented the MFCEM to teach the concepts of microbial respiration, electrochemical equilibrium and kinetics in a fuel cell, charge conservation, energy, current, and power. The senior-level bioprocess engineering course was appropriate for incorporating our MFCEM. Initial assessments based on student assignments give strong supportive evidence that the MFCEM is an effective tool for teaching multidisciplinary concepts and that active experimentation surrounding its implementation is superior to learning through a passive lecture. Expanded activities and a more rigorous learning assessment are planned for the future.

ACKNOWLEDGMENTS

The authors would like to thank the Gene and Linda Voiland School of Chemical Engineering and Bioengineering for startup funds in support of the research (Dr. Beyenal) and the Institutional Review Board (IRB) of the Office of Research Assurances at Washington State University for approving the research study and processing the exemption determination application. The authors gratefully acknowledge the U.S. Office of Naval Research (ONR) (Grant #N00014-06-1-0217) (activities through this grant laid the groundwork for the UFCM), the National Science Foundation Grant #DUE 0618872 (activities through this grant laid the groundwork for the hands-on approach and its assessment), and 3M on the development of MFCEM.

NOMENCLATURE

E_A	Anode potential (Volts)
E_C	Cathode potential (Volts)
E_M^0	Standard reduction potential of mediator (Volts)
$E_{O_2}^0$	Standard oxygen reduction potential (Volts)
F	Faraday constant (coulombs/mole of electrons)
i	Net current flow to/from an electrode (A)
i_o	Exchange current (A)
I	Current through a resistor (A)
K_s	Growth constant (g/L)
M_{ox}	Mediator concentration at oxidation state (mole/L)
M_{red}	Mediator concentration at reduction state (mole/L)
m_{in}	Inlet flow rate of fuel (moles)
n	Number of moles of electrons produced per mole of fuel
P	Power (Watt)
PEM	Proton Exchange Membrane
P_{O_2}	Partial pressure of oxygen (atm)
Q	Inlet flow rate (L/hour)
R_{ext}	External resistor (ohms)
R	Universal gas constant (J/mole/°K)
S	Substrate concentration (g/L)
S_o	Initial substrate concentration (g/L)
T	Temperature (°K)
t	Time (sec)
V	Potential drop across the resistor (Volts)
X	Cell concentration (g/L)
X_o	Initial cell concentration (g/L)
$Y_{x/s}$	Yield coefficient
ΔS	Rate of substrate consumption (g/hour)
ΔH_c	Heat of combustion of fuel (J/mole)
ε_c	Faradic efficiency
ε_E	Energy efficiency
μ	Specific growth rate (1/hour)
μ_{max}	Maximum specific growth rate (1/hour)
η	Overpotential (V)

REFERENCES

1. Felder, R.M., and R. Brent, "Designing and Teaching Courses to Satisfy the ABET Engineering Criteria," *J. Eng. Ed.*, **92**, 7 (2003)
2. Lattucha, L.R., P.T. Terenzini, and J.F. Volkwein, *Engineering Change: A Study of the Impact of EC2000, ABET Inc.*, <www. abet.org> (2006)
3. Prince, M., "Does Active Learning Work? A Review of the Research," *J. Eng. Ed.*, 1-9 (2004)
4. Dale, E., *Audio-Visual Methods in Teaching*, Holt, Rinehart, and Winston (1969)
5. Shuler, M.L., and F. Kargi, *Bioprocess Engineering Basic Concepts*, Prentice Hall, Inc. (2002)
6. Lewandowski, Z., and H. Beyenal, *Fundamentals of Biofilm Research*, CRC press, Taylor & Francis Group (2007)
7. Logan, B.E., B. Hamelers, R. Rozendal, U. Schrorder, J. Keller, S. Freguia, P. Aelterman, W. Verstraete, and K. Rabaey, "Microbial Fuel Cells: Methodology and Technology," *Environmental Science & Tech.*, **40**, 5181. (2006)
8. Lin, J.-C., H.R. Kunz, , J.M. Fenton,, and S.S. Fenton, "The Fuel Cell: An Ideal Chemical Engineering Undergraduate Experiment," *Chem. Eng. Ed.*, **38**, 38-47 (2004)
9. Tortora, G.J., B.R. Funke, and C.L. Case, *Microbiology: An Introduction*, The Benjamin/Cummings Publishing Company, Inc. (1995)
10. Bard, A.J. and L.R. Faulkner, *Electrochemical Methods: Fundamentals and Applications*, John Wiley & Sons, Inc. (2001)
11. Liu, H., and B.E. Logan, "Electricity Generation Using an Air-Cathode Single Chamber Microbial Fuel Cell in the Presence and Absence of a Proton Exchange Membrane," *Environmental Science & Tech.*, **38**, 4040 (2004)
12. Report of United Nations World Commission on Environment and Development (WCED), *Our Common Future*, Oxford University Press (1987)
13. Menicucci, J., H. Beyenal, E. Marsili, R.A. Veluchamy, G. Demir, and Z. Lewandowski, "Procedure for Determining Maximum Sustainable Power Generated by Microbial Fuel Cells," *Environmental Science & Tech.*, **40**, 1062 (2006)
14. Shantaram, A., H. Beyenal, R.A. Veluchamy, and Z. Lewandowski, "Wireless Sensors Powered by Microbial Fuel Cells," *Environmental Science & Tech.*, **39**, 5037 (2005)
15. Bloom, B.S., and M.D. Engelhart, *Taxonomy of Educational Objectives: The Classification of Educational Goals, Handbook 1:Cognitive Domain*, New York, David McKay (1956)
16. Apple, D.K., and K. Krumsieg, *Teaching Institute Handbook*, Lisle, IL, Pacific Crest (2001)
17. Golter, P.B., B.J. Van Wie, and G.R. Brown, "Comparing Student Experiences and Growth in a Cooperative, Hands-on, Active, Problem-Based Learning Environment to a Cooperative, Problem-Based Environment," Honolulu, *Conference Proceedings, American Society for Engineering Education*, 6-24, (June 2007)
18. Streveler, R.A., T.A. Litzinger, R.L. Miller, and P.S. Steif, "Learning Conceptual Knowledge in the Engineering Sciences: Overview and Future Research Directions," *J. Eng. Ed.*, 279-294 (July 2008) ❐

Industrial Scale Synthesis of Carbon Nanotubes via Fluidized Bed Chemical Vapor Deposition: A SENIOR DESIGN PROJECT

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The University of Nevada, Reno, Chemical Engineering, Capstone Senior Design class is a yearlong design experience. The first semester uses a traditional format incorporating the following concepts: process flow diagrams, piping and instrumentation diagrams, process simulation, engineering economics, heuristics, and systems engineering—multiple unit operations, environmental health and safety, engineering ethics, and teaming. During the second half of the first semester the students select design projects that continue for the following one-and-a-half semesters. One of these projects is a collaborative effort with the Center for Nanotechnology at the NASA Ames Research Center in Moffett Field, CA. The objectives for this design project were prepared in close collaboration with Dr. M. Meyyappan at NASA Ames. This particular project and the project approach have been used for two consecutive years with two different senior design teams. During the first attempt, the design effort was primarily aimed at the detailed design and economics of a 10,000 tonne per year single-wall carbon nanotube (SWNT) plant. In the second year this project was offered, the design class, besides the students' own design effort, included building a pilot-scale reactor that was used to synthesize carbon nanotubes as well as to measure selected design parameters.

The group sizes for this particular Senior Design Project ranged from three to four students. The students worked collectively to manage their own groups to meet weekly projected goals with each student acting as the group leader on a rotating basis. The weekly assignments consisted of either a brief written report or a presentation to the class. Weekly reports included updates in the following areas: literature review, experimental instrumentation, experimental results, and full-scale design calculations. At the end of the semester,

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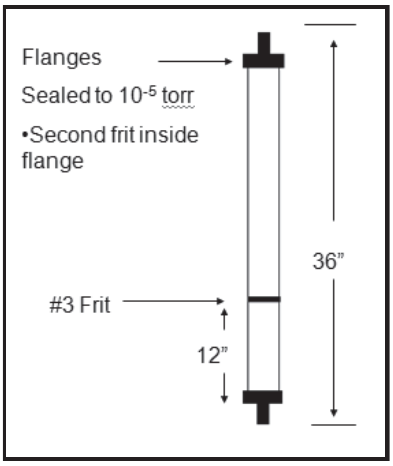
York R. Smith *recently graduated from the undergraduate chemical engineering program at the University of Nevada, Reno. He is currently a research assistant within the department where his research interests are synthesis of nano-structured metal and mixed metal oxides for photocatalytic and photovoltaic applications along with designing and engineering alternative energy systems.*



Scheme 1. *Dimensions of quartz tube used as a fluidized bed reactor for CNT synthesis.*

the students submitted a final report, PowerPoint presentation, and poster. Students presented their results at a preliminary and final design review at NASA Ames. Success of the overall project was evaluated by the students' ability to stay on task and accomplish their overall objectives of the project.

CENTER FOR NANOTECHNOLOGY AT NASA AMES RESEARCH CENTER

Started in 1996, the Center for Nanotechnology has several scientists and engineers working on various aspects of nanotechnology. The early focus was on carbon nanotubes (CNTs) because of their potential in a broad array of applications. Right from the beginning the Center has had a strong educational component through an active undergraduate student research program (USRP) and a high school student research program (HSRP) both of which are paid internship programs during the summer. Each program has had more than a hundred students in the last 10 years and a high percentage of the students have been coauthors in publications. Several of them have returned for more than one summer. NASA tracking indicates nearly 100% of the undergraduates going on to graduate school and the high school students moving on to elite universities across the United States for science and engineering. During the semester, the students are typically from the local universities. In addition, the NASA team created an "Introduction to Nanotechnology" course for engineering majors at the senior undergraduate and first-year graduate level, first taught at Santa Clara University.[1] This senior ChE design course participation is an extension of this long-standing education focus at NASA Ames.

DESIGN PROJECT

Carbon nanotubes have attracted much attention due to their extraordinary mechanical properties and unique electronic properties, and been considered for applications in electronics, sensors, instrumentation, field emission devices, flat panel displays, nanoelectromechanical systems, composites, and several others.[2] Major challenges to commercialization currently include control of diameter and hence the properties

Scheme 2. *Depiction of experimental setup. Quartz tube reactor within vertically mounted tube furnace.*

and the cost. The latter is an issue because production of even 1 kg/day of SWNTs is not common. At present SWNTs cost $500/g. Unless the production volume goes up, thus bringing the price down to a few hundred dollars per kg, their great potential will not be realized. Production of SWNTs by chemical vapor deposition covers all the "bread and butter" subjects taught in chemical engineering education: catalysis, reaction kinetics, heat transfer, fluid flow, adsorption, diffusion, and others. Future commercial production plants will be designed, built, and operated by chemical engineers.

The objective of the senior design project in collaboration with NASA was to design a process that would have the capability to synthesize 10,000 tonnes of SWNTs per year. Further, the students were also asked to design and conduct experiments to verify predictions made in their proposed design. For this design, the students chose to synthesize SWNTs using a fluidized bed chemical vapor deposition technique (FBCVD). This technique was chosen due to its ease of scalability[3] along with its practicality and costs for their experiments as opposed to other CNT synthesis techniques such as arc discharge[4-6] and laser ablation.[7] In the case of arc discharge, the scale up procedure is not evident because of the elaborate design of the system and also because the SWNT product purity is not attractive. Laser ablation is simply not scalable and practical.

EXPERIMENTAL WORK

The work of Mauron, et al.[3] along with See and Harris[8] served as an excellent review of the literature. A fluidized bed was designed and constructed consisting of a vertically mounted quartz tube (OD 40mm, ID 36mm) within a tube furnace (Thermo Scientific 21100). The tube was 36" in length and contained a porosity #3 quartz frit (14-40μm) welded 12" from one side, and a second frit of the same porosity located underneath the top sealed flange (Swagelok). A depiction of the reactor can be seen in Schemes 1 and 2.

All chemicals, magnesium oxide (MgO, Fischer Chemical, powder), ferric nitrate ($Fe(NO_3)_3.9H_2O$, Acros Organics, 99+%), ethyl alcohol (C_2H_5OH, Acros Organics, 95%), and hydrochloric acid (HCl, Fischer Chemical, technical grade) were received and used without any further treatment.

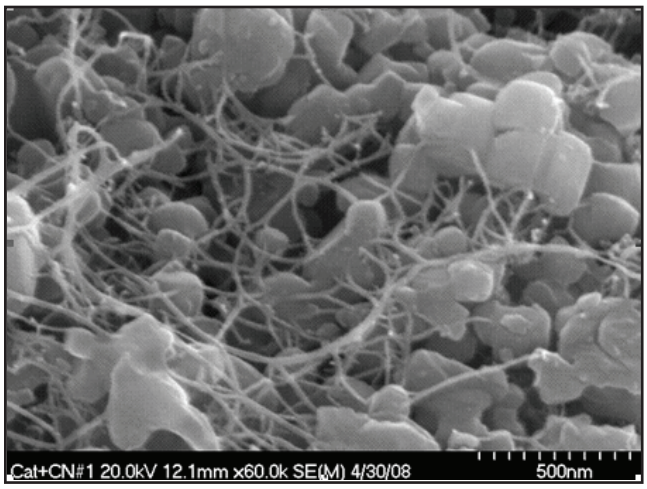


Figure 1. *SEM images of bundles of web-like CNT structures formed on iron particles through fluidized bed chemical vapor deposition at 900 ˚C for 30 minutes.*

CNT Synthesis

An iron catalyst (5 wt%) supported by magnesium oxide was homogenized in ethanol through ultrasonication. The solution was dried overnight in an air oven and ground into a fine power. A 0.5-1.0 g sample of the prepared catalyst-precursor was used to promote SWNT growth and the required gas velocity for fluidization was determined. The system was then allowed to reach the synthesis temperature of 900 ˚C - 950 ˚C while being purged with nitrogen. Once the reactor reached a temperature of 850 ˚C, methane was introduced as the carbon source and mixed with the nitrogen stream at a rate well under the explosive limit of the exit gas stream.[9, 10] The reactor was operated at 900 ˚C for one hour unless otherwise specified.

Separation of the nanotubes from the catalyst-precursor was performed in 0.1M HCl bath while stirred for 15 hours at 75 ˚C.[11] The cleaved nanotubes were decanted from solution and allowed to dry in air. The products were then analyzed through energy dispersion spectroscopy (EDS) and scanning electron microscopy (SEM) techniques.

Health and Safety

A major pedagogical issue for the students to understand was that health and safety issues are paramount. Because it

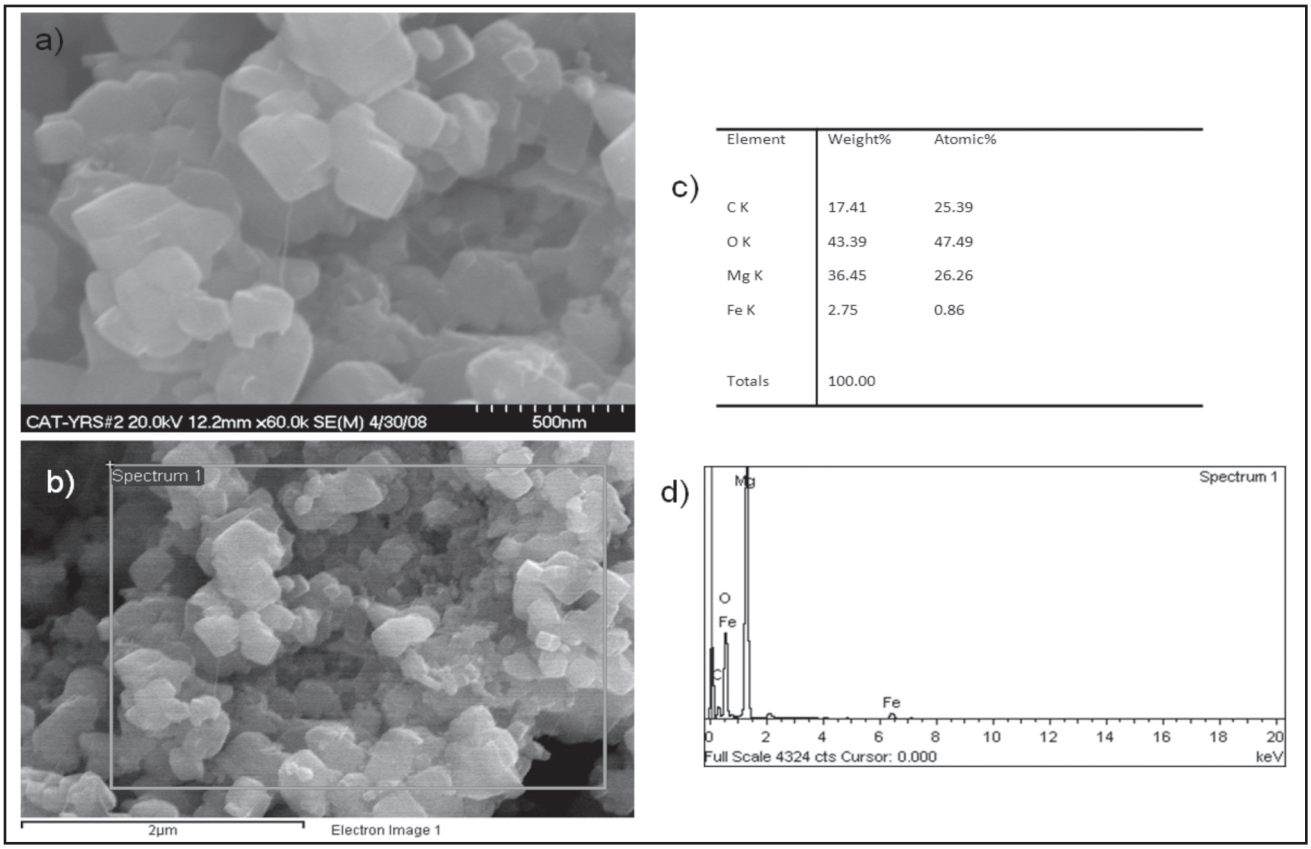


Figure 2. *SEM and EDS of CNT formed on iron particles through fluidized bed chemical vapor deposition at 900 ˚C. (a) SEM image of CNT bundle ~10 nm in diameter, (b) EDS spectrum zone, (c) and (d) EDS results.*

was necessary to deal with explosive gases at high temperatures, many safety precautions were taken. The students were required to have their experimental design approved by the Environmental Health & Safety Department (EH&S). In addition, a hazard and operability (HAZOP) analysis was done by the students and approved by EH&S before any experiments were conducted. These operating conditions and procedures were also incorporated into their full-scale design.

EXPERIMENTAL RESULTS

Fluidized Bed Reactor Experiments

Figures 1 and 2 show from SEM images that carbon nanotubes formed web-like structures across the surface of the iron catalyst. The diameters of these nanotubes have a large variation, which indicates that MWNTs along with bundles of SWNTs could have been formed. Energy dispersion spectroscopy (EDS) indicates that the web-like formations are indeed carbon deposits. SWNTs have diameters within the range of a few nanometers, which is beyond the resolution of the SEM. Further characterization techniques such as Raman spectroscopy and/or high-resolution tunneling electron microscopy (HRTEM) would confirm the nanotube morphology.

DESIGN METHODOLOGY

The sizing and fluidized bed characteristics for the industrial scale reactor were determined following the texts of Kunii and Levenspiel and Geldart.[12, 13]

Reaction Kinetics and Bed Sizing

Methane (CH_4) as carbon source and an iron catalyst supported by magnesium oxide (MgO) were chosen in this project. For a low carbon-to-hydrogen ratio, methane is ideal for SWNT production. A kinetic model was adapted from the work of Pinilla, et al.,[14] which provided a reaction rate as a function of partial pressure of methane for carbon formation of different carbonaceous catalysts at 800-900 °C. This study also provided a pseudo steady-state activation energy of 230 kJ/mol.

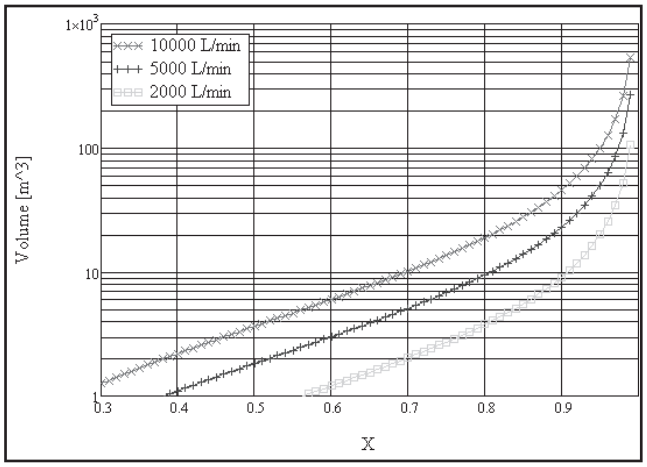


Figure 3. *Volume of fluidized bed reactor (m^3) as a function of reaction conversion (X) for various volumetric flow rates of gas.*

When sizing a fluidized bed reactor, application of a CSTR design equation can be implied. This type of model is a good estimate since it can account for distribution of particles as well as the residence time. The design equation for a CSTR is given by:[15]

$$V\frac{dC_{CH_4}}{dt} = F\left(C_{A0} - C_A\right) + r_A V \tag{1}$$

where V is the reactor volume, F is the volumetric flow rate, r_A is the reaction rate and C_{A0} and C_A are the initial and exit concentrations of the methane, respectively. To solve for the reactor volume, Eq. (1) was solved for steady-state operation and the reaction rate was solved by Eq. (3),

$$V = \frac{FC_{A0}X}{-r_A} \tag{2}$$

$$r_A = -k_0 e^{\left(\frac{-E}{RT}\right)} p_A \tag{3}$$

where X is the conversion factor, E is the activation energy, R is the gas constant, p_A is the partial pressure of methane, T is temperature, and k_0 is the reaction rate constant that was back-calculated by linearization of the Arrhenius equation[15] and use of the pseudo steady-state Arrhenius plot for carbon formation over carbonaceous catalyst with methane gas[14] on the basis of 1.5 g of catalyst/0.5 g of CNT.[3]

As prescribed by Fogler,[15] the design equation for the volume of a CSTR is determined from the following parameters: reaction rate equation, stoichiometric constants, gas concentration, and pressure. Eq. (2) was used to solve for the reactor volume as a function of conversion for various volumetric flowrates since the reaction is also a function of partial pressure, which is given in Figure 3. The minimum fluidization volumetric flowrate of gas was found to be 7,000 L/min. With a conversion of 90% this correlates to a ~50 m^3 reactor volume. These values were determined through iterating a system of nonlinear equations derived from the Ergun equation to determine the bed characteristics (discussed later). Convergence of the system of equations was achieved via a Levenberg-Marquardt algorithm implemented in a program written in Mathcad 13.

Although a CSTR model is a fair approximation, this model is normally used for a homogeneous system. This is not the case for a fluidized bed reactor that is a heterogeneous system consisting of solid and gas phases. For a first-order, solid-catalyzed, gas-phase reaction, a model presented by Kunii and Levenspiel[12] expresses the rate per unit volume of catalyst,

$$\frac{-1}{V_s}\frac{dN_A}{dt} = K_r C_A \tag{4}$$

$$K_r \left[=\right] \frac{m^3 gas}{m^3 solid \cdot s}$$

where K_r is the reaction rate constant and V_s considers the solid as nonporous. Given a feed rate v of reactant gas C_{A0} to a catalyst bed containing solids of volume V_s, integration gives Eq. (5) in terms of the outlet concentration C_{Ai} or the outlet fractional conversion X, and the reactor ability is given in Eq. (6).

$$1 - X = \frac{C_{A0}}{C_{Ai}} = \frac{1}{1 + K_r \tau} \tag{5}$$

$$\tau = \left(\frac{volume\_of\_catalyst}{volumetric\_flow\_of\_gas} \right) = \frac{V_s}{v} \tag{6}$$

This leads to the dimensionless reaction rate group of,

$$K_r \tau = K_r \frac{L_i \left(1 - \varepsilon_i\right)}{u_o} \tag{7}$$

where L is height of bed, ε is void fraction of the bed, u_o is the superficial gas velocity (actual operation) and the subscript i can be the values of fluidization or minimum fluidization. From the dimensionless rate group of Eq. (7), the height of the bed can be determined and from choosing a cross-sectional area, the volume can be approximated.

TABLE 1
Summary of Results for Minimum Fluidization Properties of Industrial-Size Fluidized Bed Reactor

A_r	Archenemies number [dimensionless]	295
Re_{mf}	Reynolds Number of minimum fluidization [dimensionless]	0.331
u_{mf}	Gas velocity of minimum fluidization [m/s]	0.025
u_o	Superficial gas velocity [m/s]	0.125
BE	Bed expansion [m]	1.06
L_{mf}	Bed height of minimum fluidization [m]	10.5
ε_{mf}	Void fraction of minimum fluidization [dimensionless]	0.45
Δp	Pressure drop [psi]	30

TABLE 2
Summary of Single Particle Calculations for Our Catalyst and Feed Gas

u_t	Terminal particle velocity [m/s]	0.62
C_D	Coefficient of drag [dimensionless]	5.82
Re_p	Particle Reynolds Number [dimensionless]	8.22

This method has been shown to correlate very well with experiment.[12] Furthermore, this correlation can be adjusted to incorporate deactivation of the catalyst. Through both these models an appropriate volume can be determined for optimal operation and cost.

Bed Characteristics

In fluidized bed calculations, different classifications of fluidized powders have different correlations. These powders are classified in terms of their particle size and the density difference of the fluidizing media. Given the density difference of the fluidized catalyst precursor and the fluidizing gas that is a mixture of methane and nitrogen, and estimating the mean particle size to be 120μm, it was found from the Geldart chart to fall within the regime of a Geldart Group B powder.[13] Sand typifies this type of powder classification that contains most solids in the mean size and density range of 60 μm < d_p < 500 μm when ρ_p = 4 g/cm^3 which has been widely investigated. An advantage to this classification of powders is that in contrast to Group A (smaller and finer particles), interparticle forces are negligible and bubbles begin to form at or near the minimum fluidization velocity.[13] It is also assumed that this material has a sphericity of ~0.8. From this calculation a sphere of equivalent volume is calculated and a new particle diameter of 108 μm is used in calculations.

To determine the fluidization characteristics, a series of nonlinear equations derived from the Ergun equation must be solved simultaneously. A summary of the minimum fluidization constants is given in Table 1 for a reactor of diameter of 2.5m, height of 10m which yields a volume of ~50m^3.

Since the desired reactor temperature is 800 – 900 °C, the density of the methane-nitrogen mixture was calculated using the Peng-Robinson equation of state for a binary system, along with other thermodynamic values such as enthalpy, entropy, compressibility, and fugacity.

An important calculation in designing fluidized bed reactors is to ensure that particle entrainment occurs. This determination is used to design the freeboard space required along with the gas distributor. These calculations are first determined by examining single-particle calculations. A summary of these is given in Table 2. Once the gas velocity exceeds the terminal velocity of a single particle, entrainment is likely to occur. Since one cannot physically account for every particle, determination of the suspension bed expansion

TABLE 3
Summary of Results for Determining Bed Suspension

ε_{max}	Maximum void fraction [dimensionless]	0.785
u_f	Actual superficial velocity of gas [m/s]	0.07
u_{ps}	Actual superficial velocity of particles [m/s]	0.055
Q_f	Superficial gas volumetric flowrate [m^3/min]	16.23

is required. The single particle calculations can be used to determine the relationship between settling flux and suspension concentration. If $u_f > u_{ps}$ entrainment is likely to occur and the bed will operate in a stable condition. This relation is shown in Table 3.

When designing the gas distributor, minimal pressure drop across the distributor is required while still maintaining fluidization. Through design criteria based on reactor dimensions, the data obtained indicate that the process would require very high natural gas demand.

Further characterization and design would include more detailed mass and energy balances on the reactor and eventually computational fluid dynamic (CFD) calculations should be used to determine the overall feasibility of this process. An economic analysis was conducted using the aid of the program CAPCOST®[16] for equipment and operating costs. By implementing a rudimentary balance sheet of income vs. expenses it is estimated that the break-even cost for SWNT by implementing this design is ~$300/kg for a production of 10,000 tonne per annum. To account for annual inflation and to achieve a profit margin of 15-20% before tax, a market selling price was estimated around $350-$400/kg. Further economic and market analysis is required, however, to determine how readily the current market would be captured, thus diluting the current market price. This analysis would yield whether or not the process would be profitable. In addition to the results presented, the designs of the catalyst synthesis and separation processes were included, but are not presented in this paper.

CONCLUSIONS

Senior-year chemical engineering students designed a process that would produce 10,000 tonnes of SWNTs per year and also conducted bench-top experiments to synthesize SWNTs. This was an excellent pedagogical experience for the students because it related to real-world design issues. The success of the students' project was evaluated on the basis of completion of weekly assignments and project milestones. The experiments resulted in carbon nanotubes, which were characterized using SEM. Detailed design of the reactor was presented, and the break-even cost of the nanotubes is estimated to be approximately $400/kg.

ACKNOWLEDGMENT

The authors acknowledge support from the Nevada NASA Space Grant Consortium for this project and diligent work by the 2007 senior design class students: Oliver Daniel, Kevin Farley, Cherish Hoffman, and Jeff Nicholson and the 2008 senior design class students: Jignesh Patel, Kylen Smith, and York Smith.

REFERENCES

1. Meyyappan, M., "Nanotechnology Education and Training," *J. Mat. Educ.*, **26**, 311 (2004); also see, Meyyappan, M., "A Course on Introduction to Nanotechnology for Undergraduate Science and Engineering Majors," in *Nanoscale Science and Engineering Education*, Sweeney, A.E., and S. Seal, (Eds.) American Science Publishing (2008)
2. Meyyappan, M., (Ed.), *Carbon Nanotubes: Science and Applications*, CRC Press, Boca Raton, FL (2004)
3. Mauron, P., C. Emmenegger, P. Sudan, P. Wenger, S. Rentsch, and A. Züttel, "Fluidized-bed CVD Synthesis of Carbon Nanotubes on Fe^2O^3/MgO," *Diam. Relat. Mater.*, **12**, 780 (2003)
4. Iijima, S., "Single-Shell Carbon Nanotubes of 1-nm Diameter," *Nature*, **354**, 56 (1991)
5. Bethune, D.S., C.H. Kiang, M.S. de Vries, G. Gorman, R. Savoy, J. Vasquez, and R. Beyers, "Cobalt-Catalysed Growth of Carbon Nanotubes With Single-Atomic-Layer Walls," *Nature*, **363**, 605 (1993)
6. Journet, C., and P. Bernier, "Poduction of Carbon Nanotubes," *Appl. Phys. A*, **67** (1998)
7. Guo, T., P. Nikolaev, A. Thess, D.T. Colbert, and R.E. Smalley, "Catalytic Growth of Single-Walled Nanotubes by Laser Vaporization," *Chem. Phys. Lett.*, **243**, 49 (1995)
8. See, C.H., O.M. Dunens, K.J. MacKenzie, and A.T. Harris, "Process Parameter Interaction Effects During Carbon Nanotube Synthesis in Fluidized Beds," *Ind. Eng. Chem. Res.*, **46**, 7686 (2008)
9. Air Products, MSDS Report, <http://avogadro.chem.iastate.edu/MSDS/methane.pdf> Accessed June 11, 2008
10. Air Products, MSDS Report, <http://avogadro.chem.iastate.edu/MSDS/hydrogen.pdf> Accessed June 11, 2008
11. Daenen, M., R.D. de Fonw, B. Hammes, P.G.A. Janssen, K. Schouteden, and M.A.J. Veld, *The Wondrous Wold of Carbon Nanotube Technologies 'A Review of Current Carbon Nanotube Technologies,'* Eindhover University of Technology & Phillips NAT-Lab (2003)
12. Kunii, D., and O. Levenspiel, *Fluidization Engineering*, 2nd Ed., Stoneham, MA, Butterworth- Heinemann (1991)
13. Geldart, D., *Gas Fluidization Technology*, John Wiley & Sons, New York (1986)
14. Pinilla, J.L., I. Suelves, M.J. Lazaro, and R. Moliner, "Kinetic Study of the Thermal Decomposition of Methane Using Carbonaceous Catalysts," *Chem. Eng. J.*, **138**, 301 (2008)
15. Fogler, H.S., *Elements of Chemical Reaction Engineering*, 2nd Ed. Prentice Hall International (2005)
16. Turton, R., R.C. Bailie, W.B. Whiting, and A. Shaeiwitz, *Analysis, Synthesis, and Design of Chemical Processes*, 2nd Ed., Prentice Hall International (2002) ❒

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 500 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.

SKITS, STOCKINGS, AND SENIORITIS ALE: CREATIVE CHEMICAL ENGINEERS

Lisa G. Bullard
North Carolina State University

I teach almost all of our students in both their first and last chemical engineering courses (Material and Energy Balances and Senior Design II). Each semester I offer them an opportunity to be creative and to reflect on their experience in these courses:

> *You may earn up to 10 points of extra credit on your final homework assignment by submitting a creative expression of your experience in this class. This might include a poem, video, craft, song, puzzle, artwork—the sky's the limit! Your work must be original, and your submission must be in good taste.*

Submissions range from simple haikus to more elaborate written works such as "All I Need To Know I Learned in CHE 205," "If Hansel and Gretel Were Chemical Engineers," and "Murder at Miskatonic—Passion, Intrigue, and Material Balances: A Play in Two Acts" (which the student later published).[1] Other students have submitted music videos with words set to songs such as "I Will Survive" or the theme to *Gilligan's Island*; craft items (jewelry, crocheted scarves featuring thermodynamic symbols, metalwork, woodwork); CHE-themed bumper stickers; original T-shirts; a bottle of homebrewed "Senioritis Ale" with a creative label; a piñata decorated to look like their Felder and Rousseau textbook, *Elementary Principles for Chemical Processes*; a decorated Christmas stocking containing slips of paper on which each student wrote their favorite memory of the material and energy balances class; and artwork ranging from cartoons to collages. Edible submissions such as cookies decorated with key equations or thermodynamic symbols are always well received. Examples of student submissions can be found at <http://www.che.ncsu.edu/bullard//Creative.htm>.

When one student group in Senior Design II assembled a "senior slide show," which was also shown at the graduating senior banquet, a new tradition was born. Now I specifically request that a group of students volunteer to take on this project each year. Some of the students voluntarily do the same sort of thing in other courses. Two students who did a music video in the stoichiometry course did sequels in process simulation, thermodynamics, and senior design that are enshrined on YouTube (<http://www.youtube.com/watch?v=8OZhEclvpFA>). Another student who submitted a personal course journal in the sophomore course continued the journal through her senior year, documenting her entire experience in chemical engineering. For examples of other ways to incorporate creativity, Felder offers ideas for integrating creativity exercises in courses throughout the curriculum,[2] and Lane shares (and performs) songs that reinforce course concepts.[3]

This assignment encourages students to reflect on their experience in the course and to attempt to express that experience in a tangible way. It provides an outlet for those students with a creative bent to express their individuality, hopefully dispelling the stereotype that engineers aren't creative. Finally, sharing the extra-credit submissions on the last day of class ends the semester on a positive and often humorous note and serves to create an indelible memory for both the students and the instructor.

REFERENCES

1 Vestal, J.M., "Murder at Miskatonic—Passion, Intrigue, and Material Balances: A Play in Two Acts," *Chem. Eng. Ed.*, **42**(2), 62-68 (2008)
2 Felder, R.M., "On Creating Creative Engineers," *Eng. Ed.*, **77**(4), 222-227 (1987), < http://www.ncsu.edu/felder-public/Papers/Creative_Engineers.pdf>
3 Lane, A.M., "Teaching Tips: Celebrating ChE in Song," *Chem. Eng. Ed.*, **42**(1), 52 (2008) ❐

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  - 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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