CEE

chemical engineering education

VOLUME 44 • NUMBER 4 • FALL 2010

Chemical Engineering Division, American Society for Engineering Education

American Institute of Chemical Engineers

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.

TIPS ON EFFICIENT, EFFECTIVE, STUDENT-CENTERED TEACHING

LISA G. BULLARD
North Carolina State University

Several excellent resources contain teaching tips.[1–4] Besides helping faculty improve their classroom environment and their students' learning, some of the recommended strategies enable instructors to better manage their time. Listed below are some techniques that have helped me to teach both more effectively and more efficiently:

- **Class Notes:** *Using "notes with gaps" provides the instructor with maximum flexibility regarding coverage and pace. The instructor can use these materials across a wide spectrum of active learning activities to transform students from scribes to active participants who actually have time to think and process material during class. Additionally, if students must be absent, the instructor can send the day's notes with the gaps filled in. An example of the student version of handouts for the material and energy balance course is posted at <http://www.che.ncsu.edu/bullard/MEB_resources/MEB.htm>.*
- **Lecture Materials:** *If you are asked to teach a course for the first time, chances are someone in your department has taught it before! Rather than generate your own notes from scratch for the first iteration, ask colleagues if they would be willing to share their course materials and use those materials as your starting point. MIT Open Courseware offers lecture notes, assignments, exams, and multimedia content for both undergraduate and graduate chemical engineering courses.[5] Also, materials for several ChE courses are available for general use at <http://www.che.ncsu.edu/bullard/>.*
- **Common Communications:** *Instructors typically send a predictable set of e-mails during the course of the semester. Keeping a file of these "standard" notes saves time in future offerings and helps ensure that you include everything important in your messages.*
- **Student Names:** *Connecting with students, particularly in a large class, is a challenge, and it becomes both more difficult and more important as the class size grows. Develop a process to learn your students' names regardless of how big the class may be. Students are often shocked to realize that an instructor knows who they are, and research shows that they are more motivated to attend class, study hard, and not cheat in classes taught by such instructors.*
- **Early Chats:** *One of my colleagues conducts 10-minute individual interviews with each student early in the semester outside of class to get acquainted. Since time for this can be prohibitive in larger classes, another option is to provide students with your one-page biography, say a few things about it on the first day of class, and ask them to give you their one-page biographies in the next class. Noting their interests and career goals can help you later connect with them individually.*
- **Common Questions:** *Address common questions by providing specific information in the syllabus. Clearly stated policies on late homework and missed tests can minimize the subsequent need for frantic e-mails and time-consuming negotiations.*
- **At-Risk Students:** *Intervene early in cases of students with low test scores or poor attendance to "catch" students who might otherwise fall between the cracks. This is especially important in large classes. Contact students who get below a certain score on your first test and ask them to meet to identify issues that may be affecting their performance. Reaching out to struggling students early sends a clear message that you care about them and want them to be successful, and that knowledge often helps them turn things around.*
- **Team Assignment and Evaluation:** *If students complete assignments in teams, Team-Maker and CATME (<www.catme.org>) are helpful tools that automate the formation of teams based on instructor-assigned criteria. In addition, you can use the same program to collect and analyze peer evaluations of team members' contributions.*

REFERENCES

1. Wankat, P., *The Efficient, Effective Professor: Teaching, Scholarship, and Service*, Boston: Allyn and Bacon (2001)
2 McKeachie, W.J., *McKeachie's Teaching Tips: Strategies, Research, and Theory for College and University Teachers*, 12th Ed., New York: Houghton Mifflin Harcourt (2006)
3 Felder, R.M., *Resources in Science and Engineering Education. <http://www.ncsu.edu/effective_teaching>*
4 Keith, J.M., D.L. Silverstein, and D.P. Visco, Jr., "Ideas to Consider for New Chemical Engineering Educators: Part 1 (Courses Offered Earlier in the Curriculum)," *Chem. Eng. Ed.*, **43**(3), 207 (2009)
5 MIT Open Courseware, *<http://ocw.mit.edu/OcwWeb/Chemical-Engineering/index.htm>* ❒

Educating Engineers. Designing for the Future of the Field

by Sheppard, S.D., K. Macatangay, A. Colby, and W.M. Sullivan

The Carnegie Foundation for the Advancement of Teaching, Jossey-Bass, San Francisco, 2009, ISBN 978-0-7879-7743-6.

Reviewed by
Phillip C. Wankat
Purdue University

This book aims very high and calls for a complete restructuring of engineering education by focusing this education on what engineers do in practice. The authors make strong arguments that this restructured education would result in a superior education for new engineers. Unfortunately, *Educating Engineers* doesn't show how this complete restructuring can occur.

Part 1 explores the historical basis and shortcomings of engineering's current engineering-science based curriculum. Then the next four parts (15 chapters, approximately 140 pages) describe what the authors learned by extensive visits to 11 electrical and mechanical engineering programs at six engineering schools. The authors selected electrical and mechanical engineering because over half of engineering graduates are in these two fields. [The vast majority of the observations also apply to chemical engineering.] The four parts are: 2. engineering science courses, 3. laboratory, 4. design, and 5. the development of engineering professionalism and ethics. If a reader is not familiar with how engineering science, laboratory, and design are usually taught and some of the best practices in teaching these courses, then these parts will be of interest. Unfortunately, the authors often name schools or professors that use a method instead of citing readily available sources (*e.g.*, line drawing as an ethical method.)

Part 5, in particular Chapter 16, "A Foundation for Professional Practice," is an eloquent description of the need to inculcate the core professional and ethical values in engineering students, including chemical engineering students. If you look at no other part of this book, go to the library, check out this book, and read the six pages of chapter 16. Although the authors' argument clearly points out that ABET's criterion for ethics should include behaving in an ethical fashion, this conclusion is never stated. Reading chapter 16 may encourage you to read the remainder of Part 5 that strongly supports the need for professional education throughout students' studies.

Part 6 on changes in engineering education is meant to be the message and heart of the book. This part is in agreement with other studies that engineering education needs to change. Chapter 21, "Usable Knowledge," my second favorite chapter, is a succinct and useful review of learning principles. It reinforces the point that students will learn engineering science better if it is imbedded in engineering practice that can be, but often is not, brought to the fore in laboratory, design, and professional courses. The authors explain how service learning can help provide links to engineering practice, but miss the opportunity to discuss in detail the obvious advantages of co-operative education and internship programs that closely link industrial practice to the undergraduate curriculum.

Chapter 21 also compares the changes needed in engineering education to the ongoing changes in medical education. Exploration of these similarities is useful and probably novel for most readers. Unfortunately, the differences between medical education, which is a graduate-level program for a licensed profession, and engineering education, an undergraduate-level program for an essentially unlicensed profession, are not delineated. Information from the learning sciences on how people learn shows that people learn complicated activities such as engineering by doing. The authors advocate a "cognitive apprenticeship" that would have repeated cycles of: 1. modeling, 2. scaffolding (providing support), 3. coaching with feedback, and 4. fading (removing support).

Chapter 22 proposes an integrated, spiral curriculum, but the authors cite no examples and were apparently unfamiliar with chemical engineering examples of spiral curricula (*e.g.*, at WPI). The core of the proposed curriculum is professional practice of engineering. Chapter 23 briefly discusses approaches and pitfalls to development of this new curriculum. Unfortunately, the well-entrenched faculty-reward structure at research universities that rewards research and research contracts much more than pedagogical innovations and teaching the professional practice of engineering is essentially ignored.

What could be done to make the second edition a *tour de force* that shows not only that restructuring is needed, but also shows how restructuring can be done? First, follow Boyer's lead in Scholarship Reconsidered (a Carnegie Foundation book that did remake the academic landscape) by including hard data in addition to observation data. Since engineers eat and drink hard data, its inclusion will make the book more convincing. Second, explicitly discuss the scalability of pedagogical methods. Third, delineate necessary changes in accreditation and other constraints. Fourth, address the enormous barrier to change caused by the current reward structure at most universities. Finally, consider if the public would be better served if engineers had to have a graduate degree before meeting required licensing requirements. ❐

Chemical Engineering Education

Volume 44 Number 4 Fall 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).***

Pilot-Scale Laboratory Instruction for ChE:
THE SPECIFIC CASE OF THE PILOT-UNIT LEADING GROUP

Anne-Marie Billet, Séverine Camy, Carole Coufort-Saudejaud
University of Toulouse • Toulouse cedex 4, France

Laboratories are considered a fundamental part of the student's educational experience in engineering. In the case of chemical engineering, students implement theories and concepts that are related to mass, heat, and momentum transfer. From an educational point of view, Feisel and Rosa[1] have listed the main 13 objectives of engineering instructional laboratories: 1) instrumentation practice, 2) identification of models, 3) conducting experiments, 4) data analysis, 5) design application, 6) learning from failure, 7) use of creativity, 8) improvement of psychomotricity, 9) safety consideration, 10) efficient use of communication, 11) teamwork experience, 12) consideration of ethics (for lab), and 13) sensory awareness. During the lab session, students are usually divided into small groups, and perform laboratory or pilot-scale unit operations experiments under the direction of professors or associate teachers. Students sometimes content themselves with following the steps that are described in the protocol they have been given and do not try to deeply understand the underlying phenomena. This kind of behavior is often said to be a "cookbook" or "follow the recipe" approach, as pointed out by McCreary, et al.[2] and Young, et al.[3] As a consequence, students lack motivation for practical work and this leads to poor output, *i.e.*, to inefficient teamwork (as students are not eager to take on responsibilities) and rather poor analysis of the experimental results, among other undesirable outcomes. Assuming such behavior, the objectives suggested by Feisel and Rosa[1] are far from being fulfilled. To attempt to correct the deficiencies of such teaching, increase retention of knowledge, and improve integration of concepts, different types of laboratory instruction have been suggested. In his review, Domin[4] distinguishes four different styles of teaching (expository, inquiry, discovery, and problem-based) that can be differentiated according to three distinct descriptors (outcome, approach, and procedure). He concludes that the differences

***Anne-Marie Billet** completed her engineering degree and her Ph.D. thesis in process engineering at* "Institut National Polytechnique" *in Toulouse (France) in 1992. She is now an associate professor in the Engineering school (French 'grande école') INPT-ENSIACET (Toulouse, France), in the Chemical Engineering Department. She carries out research activities at the* Laboratoire de Génie Chimique *(Toulouse, France) in the field of hydrodynamics and mass transfer in bubble reactors.*

***Séverine Camy** obtained her undergraduate degree and M.S. in chemical engineering in 1997 and her Ph.D. in chemical and process engineering in 2000, from the* Institut National Polytechnique de Toulouse *(INPT). She joined ENSIACET at the University of Toulouse as an associate professor in 2006. She carries out her research at the* Laboratoire de Génie Chimique *in Toulouse on the topic of supercritical CO_2 separation and reaction processes.*

***Carole Coufort-Saudejaud** completed her engineering degree in 2001 and her Ph.D. in chemical engineering at the* Institut National des Sciences Appliquées *(INSA Toulouse, France) in 2004. Since 2006, she is an associate professor of chemical engineering at* Ecole Nationale des Ingénieurs en Arts Chimiques et Technologiques *(Toulouse, France). Her research interests are the analysis and the optimization of fluidized bed chemical vapor deposition processes at the* Laboratoire de Génie Chimique *(Toulouse, France).*

between styles lead to different learning outcomes. In a more pragmatic point of view, Birol, et al.,[5] suggest that cross-course projects can be followed; Jimenez, et al.,[6] propose to focus on open-ended problems within a "stop and go" course organization—a method that requires students to search for information, to plan experiments, to interpret data, and to derive conclusions. Doskocil[7] recommends combining the design of experiment techniques with a current experiment to present a more "real world" situation to the student. Felder and Brent[8] enthusiastically promote active learning. Based on the game show "Survivor," Newel[9] also recommends a method for active learning that addresses students' involvement. From the literature on chemical engineering laboratory education, one can see that most of studies are devoted to points 1 to 9 in Feisel and Rosa's list while the four last points—which are related to communication and management—are scarcely tackled. As pointed out by Jones,[10] Smith,[11] and Johnson and Johnson,[12] however, generic skills such as team management and time management should not be taught only during key-note lectures; they also have to be experienced first-hand.

Lab work dedicated to chemical engineering practice at INP-ENSIACET is traditionally performed in a specific platform that gathers various chemical engineering pilot-scale rigs (<http://aigep.inp-toulouse.fr/pages/page_accueilpag.html>) such as: batch and continuous distillation, liquid-liquid extraction, batch reactor, stirred tank with gas-liquid mass transfer, multiple effect evaporator, gas absorption columns, and heat exchanger. The objective of this lab experience is to have students discover and operate the instrumentation and equipment related to the main chemical engineering operations. Traditional lab practice, however, has shown some weaknesses when derived through the traditional laboratory instruction and this has prompted some instructors to propose an innovative process for managing laboratory instruction. As a result, the idea of a "pilot-unit leading group" for the chemical engineering pilot-scale laboratory instruction was introduced.

The aim of this paper is thus to present the pilot-unit leading group approach that teachers of INP-ENSIACET have put into practice for chemical engineering laboratory instruction.

PRESENTATION OF THE CONCEPT AND PRACTICE OF PILOT-UNIT LEADING GROUP

The students involved are in the second year of INP-ENSIACET engineering formation (Chemical Engineering Department); this corresponds to the first year of a Master's program. Students spend six full days in the pilot equipment platform. To ensure that the students fully benefit from these six days, technical and pedagogical booklets are given to them a few days before the beginning of the lab session. Students are expected to read them, to recall the specific theory that they have been taught on the subjects, and to bring with them any documents that may be helpful during the lab session.

Pedagogic Objectives

The pilot-unit leading group approach has a dual purpose:

1. The first is rather classical and aims at integrating the concepts learned in the classroom into a coherent learning activity,

2. The second aims at adding some communication and management skills into the curriculum. The difficulty of this dual approach is integrating the second objective without withdrawing the requirements of the first objective. As pointed out by Box, et al.,[13] one way to fulfill this goal is to include a shift in the control and responsibility of learning from teacher to student, and to promote active participation by the learner. To create such a dynamic learning environment, the educational team at INP-ENSIACET decided to transfer or partially delegate the responsibility of instruction for the pilot-units to the students and let them manage their classmates.

At the end of the laboratory session, the assessment must show that students:

- *have identified and applied relevant chemical engineering theory to the apparatus,*
- *have conducted an extensive and detailed investigation of the pilot plant operation,*
- *have gathered, carefully examined, and interpreted the data,*
- *have drawn consistent conclusions,*
- *have made recommendations based on technical and scientific aspects, and*
- *have developed skills in writing technical reports, oral and written communication, management of groups, and teamwork.*

Practical Organization

The class is divided into six groups of three or four students who work on six pilot-scale operations: liquid-liquid extraction, continuous distillation, batch distillation, absorption, stirred tank, and multiple effects evaporator. Each student group uses each pilot during one day. The pilot-unit leading group concept refers to the fact that the students become the "managers" for the pilot they have been working on during the first day of the laboratory session. As managers, they must decide which kind of experiments have to be done by the other students during the lab session, manage the other students in terms of the fixed time schedule, and answer the technical questions of their classmates.

To illustrate this concept we chose to focus on the example of a liquid-liquid extraction pilot-scale laboratory that uses water as a solvent to extract acetone from an acetone-cyclohexane mixture. The process is quite simple and consists of a 4.5 m height glass pulsed column, two feeding pumps for the solvent and the acetone-cyclohexane mixture, a pump to ensure pulsation inside the column, and several tanks for the feeds, extract, and raffinate. Students are expected to measure flow rates and the composition of the different phases using gas chromatography (GC) analysis.

Schedule of the Formation

Day 1

On the first day of the laboratory, a teacher presents the pilot-scale installation that the students have to operate. The main possible experiments that can be performed on the installation are explained. During this day, the students become familiar with the pilot plant. They analyze the apparatus and environment (instrumentation, process control, devices, analytical techniques, etc); then they perform experiments, interpret the experimental results, and put into practice both design models and tools of simulation to better understand the physical and chemical phenomena. In addition to learning the pilot operation, students spend the day in coordination with the teacher answering the different questions that arise such as:

- *How long will it take to reach a steady-state regime?*
- *How many analyses are necessary to achieve a complete characterization of the rig?*
- *How many analyses can be done by a group of four students during a single day of lab session?*
- *Are some parameters more relevant and/or more convenient to study than others?*
- *Do some operating conditions generate difficulties of operation for the pilot?*
- *Do we need to calibrate the measurement devices each day?*
- *How long do the students need to derive mass and energy balances?*

At the end of the day, the students have to give the teacher a planning sheet compiling the details (operating conditions) of the experiments they want their classmates (of the other groups) to perform. Special attention must be paid to the coherence of the operating conditions so that each group may carry out a complete study of the influence of at least one operational parameter. In particular, each group must collect a set of experiments that can be interpreted and that also contain at least one or two experiments dedicated to the repeatability and redundancy of measurements.

For example, concerning the liquid-liquid extraction laboratory, the flow rates of the feed and of solvent, as well as the pulsing frequency and amplitude, can be varied. For each set of operational conditions, students have to determine, at least, the composition of the currents (using chromatography or refractometry), the global and specific mass balances, and the number of theoretical stages using a triangular diagram. At the end of the day, the planning sheet established by the leading group must gather the operating conditions that will be tested by the other groups. This sheet must be presented using a clear and precise table that can be easily understood by the teachers and the other students.

Day 2

During the second day, students discover a new pilot-unit and have three main tasks:

1) Perform the experiments requested by the leading group of the unit on which they are working.
2) Write a report (called a basic report) concerning the results of the experiments and the analysis of the data. This report is given at the end of the day to the pilot-unit leading group of this unit.
3) Manage the group of students working on the apparatus they are in charge of. This last task includes the presentation of the apparatus, the explanation of the experimental schedule, and the management of their classmates all day long. Note that depending on the results obtained by each group, the planning sheet—which gathers the operating conditions—can be updated by the leading group at the end of each day, according to the notion of continuous quality improvement (for the so-called "Kaizen" attitude, described by Imaï and Kaizen[14]).

End of the session

One week after the last day of laboratory class, each group has to give a comprehensive report (called a pilot-unit leading group report) concerning the pilot apparatus they had to manage. This work is also evaluated by means of an oral presentation (about 20 minutes). This presentation must recall the principal parts of the report. The assessment tools will be described in part 4 of this paper.

Observed Evolution of Students' Behavior

The detailed objective of the pilot-unit leading group technique is to lead to the improvement of:

- Competencies related to investigation and analysis, as the students are expected to :
  - *conduct a literature search to collect information concerning the unit operation*
  - *design appropriate experiment schedules,*
  - *design and conduct analytical, modeling, and experimental investigations*
  - *interpret their own data and the data of other groups, and then draw conclusions*
- Competencies related to management and transferable skills. Indeed, all along the laboratory course, students experiment on how to manage a project, which makes them sensitive to their future professional experience. This is an active learning process and a real-time life experience: They have to act as an individual and as a member of a team structure; they have to share responsibilities, assign

roles among the group, define milestones and deadlines, monitor progress, and integrate the individual contributions of each group into a final deliverable (written report and oral presentation).

In addition, the pilot-unit leading group experience also delivers a strong message on aspects related to health, safety, security, and professional ethics, thus providing learning opportunities to develop specific competencies in these important skills.

The feedback of teachers who have experienced this approach, which has been applied at INPT-ENSIACET for several years, reveals different kinds of benefits for the students:

- *"During the laboratory class, students seem to be more concerned by the experiments they have to perform because their results have to be used by their classmates. For example, when there is a doubt concerning the protocol they directly refer to the 'pilot-unit leading group.' They do not hesitate to repeat an experiment that was not reliable enough. If they deviate from the given protocol, they derive in their report a discussion about the observed discrepancies."*
- *"The involvement of the leading group is excellent. They really take care of their apparatus and seriously consider the management of the other groups."*
- *"Students learn how to design and to estimate the quantity of work that can be done by their colleagues in a one-day period."*
- *"Students also experience how to delegate work to their classmates and how to manage technical staff (management of time, confidence in the results, etc.)."*

TEACHING-STAFF INVOLVEMENT/ COMMITMENT

The implementation of the pilot-unit leading group concept in the chemical engineering syllabus at INP-ENSIACET has modified some aspects of the pedagogy.

The teaching staff still has the responsibility of:

- *safety and security aspects*
- *the time schedule of the students (planning of turnover)*
- *evaluation of the relevance of operating conditions proposed by the pilot-unit leading group,*
- *evaluation of the relevance of methodologies available to address the objectives,*
- *evaluation of the assimilation of concepts learned in class.*

Some new aspects have to be taken into account, however. As pointed out by Lickl,[15] the teacher's role is not to be the "sage on the stage" but the "guide on the side." On day one of the pilot-unit leading group laboratory, the teacher's role is somewhat traditional: he/she gives explanations of the apparatus, of the relevant parameters to study, of how to run the analyses, etc. During the following days, the teacher's major role is to observe (especially concerning the security and safety aspects). The teacher must accept that the knowledge has to be delivered to a student by another student, rather than by himself/herself). The teacher must still make sure, however, that all technical aspects and fundamental theories are well transmitted, understood, and applied. As a result, the teacher is involved in discussions with the groups all day long.

A real effort has to be made by the teacher concerning possible misconceptions, which have to be checked more or less in real time. For instance, as mentioned before, the leading group can modify, at the end of each day, the planning sheet of the operating conditions in relation to the results obtained by the working group. This can only be done after a discussion with the teacher and under the teacher's agreement. Thus, this kind of pedagogy needs a high reactivity from the teacher, but the high motivation of the students is worth it!

ASSESSMENT TOOLS

Assessment of competencies acquired by the students

As previously mentioned, assessment of students' performances during pilot-scale laboratories covers several levels of skills and know-how, since the students have to produce different types of reporting during the entire laboratory instruction.

Students have to produce a basic report after each pilot-scale investigation—that means at the end of each day. Guidelines for this document are supplied to the students through a lab protocol, in which practical investigations and confrontation of their results with theoretical phenomena are demanded. The students are asked to give this report back to the teaching staff and to give a copy to the group of students (pilot-unit leading group) that is managing the apparatus they worked on. From an evaluation point of view, the objective of this basic report is to check that students have been able to perform the experiments, to observe the main physical phenomena involved, and to make a proper use of their results.

As said in the second part of this paper, at the end of the laboratories each student group also has to produce a typewritten report (referred to as the pilot-unit leading report), that contains a broad and complete analysis of the pilot-scale experiments for which they are the leading group. This report must contain several parts: a list of the industrial applications of the considered unit operation and the associated research fields, a description of the pilot-scale apparatus, the gathered experimental results of all groups, a critical and detailed analysis of the experimental results, a modeling study concerning at least one phenomenon that takes place within the pilot, and a discussion of the possible improvements that could be made to the apparatus. For this report, supplementary time (one week) is given to the students so that they can compile and analyze all data. Mainly evaluated through this work are the students' management capacity and their ability to analyze the experimental results. The students are also expected to develop critical evaluation skills on "what" and "why"; they should even suggest modifications to the pilot and lab work that would make them more efficient.

Finally, at the end of the laboratory session, the students are required to give an oral presentation (20 minutes) of their pilot-unit leading group experience. This presentation is done in front of the whole class so that every student hears a complete overview of each pilot-scale lab, even those that they have not managed. This oral presentation aims to check the students' clarity of expression and understanding, ability of technical presentations, and capacity to make a synthesis. The final mark awarded is a weighted average of the three assessments.

Details of the assessment tools are listed below:

Basic report: The evaluation of the basic report is based on specific studies that must be investigated by the students. As an example, the evaluation of students' performance for the liquid-liquid extraction laboratory is carried out using the criteria in Table 1, which has been established in connection with the guidelines supplied by the protocol.

The last topic of the assessment for the basic report leads to individual marks for the same experiment within a student group. This individual assessment can be a way of rewarding the conscientious students and of penalizing those who are less active.

Pilot-unit leading report: The assessment of the pilot-unit leading report is built on a different basis than the basic report. For the pilot-unit leading report, the degree of freedom left to the students is more important, since they have to prove their ability to gather, select, analyze, and synthesize experimental data, and this is largely dependant on their capacity to manage other groups on the pilot-scale unit they are leading. As said before, they are also encouraged to suggest in this report some modifications to improve the pilot or the pedagogical method. The criteria assessed in the pilot unit leading report are presented in Table 2. The evaluation of this report leads to a global mark for the whole group.

Oral presentation: An individual mark for each student is given from the oral presentation. During the oral presentation, students are evaluated on the criteria listed in Table 3 rather than on their technical skills and theoretical know-how that has been attained through the basic and the pilot-unit leading reports. Through the global assessment of each student during

TABLE 1
Evaluation Criteria for Basic Reports

General area	Details	Marks
Analysis of experimental results	Concentrations profiles	/4
	Steady-state achievement	
	Global residence time evaluation	/2
	Global mass balance	/2
	Solute mass balance	/2
	Saturation curve plotting	/1
	Minimum and maximum flow rates	/2
	Minimum flow rate for a specified separation	/2
	Number of theoretical plates	/2
	Evaluation of performance of separation (recovery rate, selectivity, efficiency)	/4
ProSim Plus® Software use	Simulation of extraction column	/5
	Comparison experiments/simulation	/4
Uncertainties analysis	Measurements uncertainties	/2
	Flow rates consistency	/2
Influence of operating conditions	Influence of operating conditions	/2
	Theoretical evaluation	/3
	General comments	/3
Conclusions	Over-design	/2
	Improvement proposals	/2
Practical assessment	Structure	/3
	Visual presentation	/3
Global behavior	Respect of safety instructions	/4
	Motivation/Involvement	/4
Total		/60

TABLE 2 **Evaluation Criteria for the Pilot-Unit Leading Report**		
General area	**Details**	**Marks**
General presentation	Structure	/5
	Clarity	
	Language/spelling mistakes	
Introduction/ Position of the problem	Presentation of the experiment	/5
	Identification of main physico-chemical phenomena	
	Literature study (industrial applications, technological improvements, safety recommendations, ...)	
Management of experimental investigations	Identification of relevant operating parameters	/10
	Distribution of experimental tasks to other group of students	
	Number of gathered experiments	
	Processing of gathered experimental results	
Analysis of experimental results	Repeatability of results	/10
	Uncertainties of measurements	
	Phenomenological analysis	
	Influence of operating conditions	
	Critical analysis	
	Comparison with theoretical calculations	
Critical evaluation	Pilot-scale performances evaluation (if possible)	/5
	Operability limits	
	Simulation (if possible)	
	Safety analysis (APR, HAZOP, if possible)	
General conclusions	Technical problems encountered	/5
	Suggested improvements	
Total		/40

TABLE 3 **Evaluation Criteria for the Oral Presentation**	
	Marks
Dynamism/personal implication	/4
Clarity of expression	/4
Precision of information	/4
Proper use of visual tools	/4
Ability to answer questions	/4
Total	/20

these pilot-scale laboratories, the 13 objectives defined in the previous section and listed by Feisel and Rosa[1] are finally intended to be explored.

Assessment of the instructional laboratories as seen by the students

At INP-ENSIACET, every teaching course is subjected to a final global evaluation made by the students. Students are free to respond to the survey or not; the response rate is generally greater than 90%. The objective is to obtain the students' perception of the course, to highlight any shortcomings, and thus to improve instructional and/or practical aspects. In the special case of these pilot-scale laboratories, the students were asked to respond to the questions presented in Table 4 (next page).

The six pilot-scale operations chosen for this new kind of teaching had been carefully selected for their ability to be adapted to the pilot-unit leading group concept; no influence of the type of unit operation that had to be lead during the session had been highlighted on the survey results.

As can be seen in the survey report, the application of the pilot-unit leading group approach has met rather enthusiastic reactions from students.

CONCLUSION

The development and assessment of competencies in engineering education require some innovative approaches to teaching. Through the implementation of the pilot-unit leading group approach, the chemical engineering students at INP-ENSIACET are provided with active learning activities and opportunities. It is through these activities and opportunities that several of the expected outcomes and transferable skills of the EUR-ACE[16] Framework Standards—*e.g.*, Knowledge and Understanding, Engineering Analysis, Engineering

Design, Investigations, Engineering Practice, Transferable Skills—are developed, demonstrated, and assessed. In addition, the 13 objectives for laboratory work as listed by Feisel and Rosa[1] are entirely accomplished within the learning environment.

ACKNOWLEDGMENT

The authors would like to thank the technical staff of the AIGEP platform for their valuable help during the laboratories.

REFERENCES

1. Feisel, L.D., and A.J. Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," *J. Eng. Educ.*, **94,** 121 (2005)
2. McCreary, C.L., M.F. Golde, and R. Koeske, "Peer Instruction in the General Chemistry Laboratory: Assessment of Student Learning," *J. Chem. Educ.*, **83**, 804 (2006)
3. Young, B.R., H.W. Yarranton, C. Bellehumeur, and W.Y. Svrcek, "An Experimental Design Approach to Chemical Engineering Unit Operations Laboratories, Education for Chemical Engineers," *Transactions of the IChemE Part D* (2006)
4. Domin, D.S., "A Review of Laboratory Instruction Styles," *J. Chem. Eng.*, **74**, 543 (1999)
5. Birol, G., I. Birol, and A. Çinar, "Student Performance Enhancement by Cross-Course Project Assignments: A Case Study in Bioengineering and Process Modeling," *Chem. Eng. Ed.*, **35**, 128 (2001)
6. Jimenez, L., J. Font, J. Bonet, and X. Farriol, "To the Global Chemical Engineer Through the Holistic Unit Operations Laboratory," *Chem. Eng. Ed.*, **36**, 150 (2002)
7. Doskocil, E.J., "Incorporation of Experimental Design in the Unit Operations Laboratory," *Chem. Eng. Ed.*, **36**, 196 (2003)
8. Felder, R.M., and R. Brent, "Random Thoughts: Learning by Doing," *Chem. Eng. Ed.*, **37**, 282 (2003)
9. Newell, J.A., "Survivor: A Method for Active Learning in the Classroom that Addresses Student Motivation," *Chem. Eng. Ed.*, **39**, 228 (2005)
10. Jones, D., "Team Learning Approach in Education," *J. Quality and Participation*, **19**(1), 80 (1996)
11. Smith, K., "Cooperative Learning: Making 'Groupwork' Work Using Active Learning," *New Directions for Teaching and Learning*, **67**, 71 (1996)
12. Johnson, D., and R. Johnson, *Learning Together and Alone*, Allyn and Bacon, Boston, USA (1999)
13. Box, V.J., P.R. Munroe, A.C. Crosky, M.J. Hoffman, P. Kraulis, and R.A.J. Ford, "Increasing Student Involvement in Materials Engineering Service Subjects for Mechanical Engineers," *Int. J. Eng. Educ.*, **17**, 529 (2001)
14. Imaï, M., and G. Kaizen, "L'art de manager avec bon sens," *Editions JV&DS* (1997)
15. Lickl, L., "Work in Progress—Putting Engineering Pedagogy in Europe and Asia on an International Level," *37th ASEE/IEEE Frontiers in Education Conference*, Milwaukee, WI (2007)
16. EUR-ACE Framework Standards for the Accreditation of Engineering Programmes (2005), <http://www.feani.org/EUR_ACE/PrivateSection/Documents/A1_EUR-ACE_Framework%20Standards_2005-11-17corrected.pdf> ❐

TABLE 4
Survey Results

	Disagree (%)	Somewhat Disagree (%)	Agree (%)	Strongly agree (%)
Are the objectives of each laboratory clearly defined?	0	18.2	78.8	3.0
Does the global time schedule of the laboratories match the objectives?	0	3	66.7	30.3
Is the evaluation mode clearly defined at the beginning of the laboratories?	6.1	24.2	48.5	21.2
Is the technical organization suitable?	0	2.9	64.7	32.4
Is the equipment quality sufficient?	3.2	12.9	67.7	16.1
Is the equipment quantity sufficient?	0	0	58.8	41.2
Are the supplied documents relevant?	0	0	54.5	45.5
Are the teacher's explanations sufficient?	0	6.1	60.6	33.3
Do the teachers take enough time to answer questions?	0	6.1	36.4	57.6
Do the teachers encourage your personal reasoning?	0	9.4	75.0	15.6
Are scientific or technical exchanges with the teachers enriching?	0	0	64.7	35.3
Do the laboratories give you a clear view of the domain area concerned?	5.7	17.1	51.4	25.7
Do the proposed investigations enhance your personal thinking?	2.9	2.9	54.3	40
Do the proposed investigations lead you to develop interesting know-how?	2.9	14.7	58.8	23.5
Is the assessment mode satisfying?	3.0	15.2	78.8	3.0
Did you enjoy these laboratories?	0	21.2	69.7	9.1

HEAT TRANSFER IN GLASS, ALUMINUM, AND PLASTIC BEVERAGE BOTTLES

William M. Clark, Ryan C. Shevlin, and Tanya S. Soffen
Worcester Polytechnic Institute • Worcester, MA 01609

In August 2004, the Pittsburgh Brewing Company began packaging its Iron City Lager in bottles made of aluminum rather than glass. Advertisements stated that the contents of an aluminum bottle not only got colder faster, but stayed colder longer than the contents of a traditional glass bottle.[1] Despite the fact that the thermal conductivity of aluminum is much higher than that of glass, it was claimed that an aluminum bottle would keep the contents cold for up to 50 minutes longer than a glass bottle would.[2] This claim appears to have originated from a study done in February 2004 by an un-named independent laboratory for Danzka, a Danish vodka producer that began using aluminum bottles at that time.[3] Aluminum bottles are now used by several beverage companies who maintain the "gets colder faster" claim but have dropped the illogical "stays colder longer" claim.[4,5] The myth of the insulating ability of aluminum beverage bottles persists, however, on the Web and elsewhere.

Part of the motivation for substituting aluminum for glass appears to be less product loss due to bottle breakage and lower shipping cost due to lower weight.[6] Some beverage companies have also begun using plastic bottles for these reasons as well as for safety at beaches and public events.[7] The claim has been made that plastic bottles stay cold as long as glass and longer than aluminum.[8]

There have been few published scientific studies on the thermal performance of bottles. Researchers at Bucknell University reported at the 2005 Annual AIChE meeting that the contents of aluminum bottles cooled down much faster but also heated up slightly faster than those in glass bottles.[9] Conversely, researchers at Loyolla College found that on heating in air, an aluminum bottle kept it contents colder slightly

William Clark *is an associate professor in the Chemical Engineering Department at Worcester Polytechnic Institute. He holds a B.S. from Clemson University and a Ph.D. from Rice University, both in chemical engineering. He has taught thermodynamics, separation processes, and unit operations laboratory for more than 20 years. His current research focuses on using finite element analysis for teaching chemical engineering principles and for analyzing separation processes.*

Ryan Shevlin *and* ***Tanya Soffen*** *contributed to this study as seniors in chemical engineering at WPI. This work is based in part on their Major Qualifying Project (senior thesis) completed in May 2009. Although they have now graduated and begun their professional careers, they are continuing their bottle studies with a focus on taste and enjoyment.*

TABLE 1 Properties of Materials Used							
	Inside Diameter d (m)	Effective Height z (m)	Thickness t (m)	Density ρ (kg/m^3)	Heat Capacity C_p (J/kg K)	Thermal Conductivity k (W/m K)	k / t (W/m^{2}K)
aluminum	0.059	0.174	3.81e-4	2700	900	160	420000
glass	0.060	0.168	2.03e-3	2203	703	1.38	680
plastic	0.062	0.157	3.56e-4	1350	1300	0.2	560
water				1000	4180	0.6	
air				1.205	1006	0.025	

longer than a glass bottle but explained that the two bottles behaved essentially identically because the heat transfer is controlled by natural convection and radiation at the outer surface rather than conduction through the bottle wall in this situation.[10] Calculations they made indicated that thermal conductivity of the bottle material should have little effect upon heating in air but should have a significant effect upon cooling in ice water or heating while hand-held.

In this paper we report experiments and calculations that quantify the thermal performance of glass, aluminum, and plastic bottles under various conditions and provide an interesting way to teach heat transfer principles. We measured the temperature of water in 16 oz bottles upon cooling in a refrigerator, cooling in ice water, heating in air, and heating while hand-held, and used COMSOL Multiphysics software to illustrate the appropriate heat transfer mechanisms and calculations. Although we undertook this investigation as a senior project we believe our methods and results can be readily applied to teaching heat transfer fundamentals via a course project, a laboratory exercise, or a class demonstration. While this problem has particular appeal to some students, it should be noted that students should be at least 21 years of age to appreciate it fully.

EXPERIMENTAL

Readily available 16 oz beverage bottles (Budweiser, aluminum and glass; Miller Lite, plastic) were drained, rinsed with water, and air dried. Number 3 rubber stoppers were sliced longitudinally halfway through to accommodate thermocouple wires that were extended into the bottles to a height of 4 inches from the bottom of each. Type J thermocouples were used with National Instruments interfaces connected to Labview software for continuously monitoring and recording the temperature of each bottle. The thermocouples were found to give the same readings to within 0.05 °C in ice water. Bottles were filled with 475 ml of deionized water. Weight as well as volume of each fill was carefully checked to ensure the bottles contained the same amount.

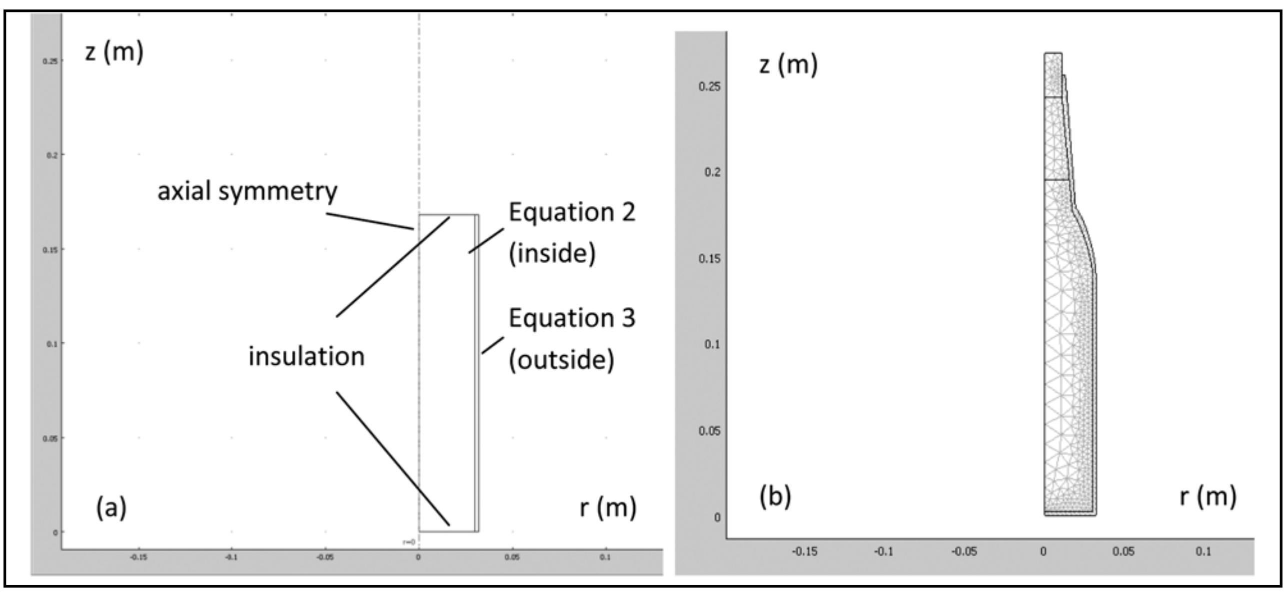


Figure 1. *2-D axially symmetric geometry of glass bottle modeled as (a) equivalent cylinder filled with water, and (b) more realistic bottle shape with air between water and rubber stopper. Boundary conditions are indicated on the equivalent cylinder model.*

A small (2 cubic ft) refrigerator that was otherwise empty was used for cooling experiments. Bottles were placed on a plastic rack and were not touching the walls or each other to minimize conduction. Duplicate measurements were made with bottles in different positions within the refrigerator to determine if bottle placement affected the results. Measurements were also made with two of the same type of bottle in the refrigerator and with two thermocouples in the same bottle. Heating in air was studied by removing the bottles from the refrigerator and placing them on a plastic rack in the room. Cooling in ice water experiments were conducted by simply submerging each bottle up to the neck in an ice water bath. Heating while hand-held experiments were conducted with one person holding one bottle in each hand after the bottles were removed from the ice water bath. Over the course of the experiment, the subject placed the bottles on a shelf intermittently, rubbed the hands together to warm them, and alternated which hand held which bottle, but care was taken to ensure that each bottle was held for the same length of time.

ANALYSIS

We assume that the bottles can be considered as cylinders of the appropriate diameters with the heights adjusted to yield volumes of 475 ml. The measured inside diameters and the effective heights of the bottles are shown in Table 1. Heat transfer through the bottle material can be described by

$$\rho C_P \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T \tag{1}$$

with boundary conditions at the inside and outside walls given by:

$$-k \left.\frac{\partial T}{\partial r}\right|_{r=R_i} = h_i \left(T - T_i\right) \tag{2}$$

$$-k \left.\frac{\partial T}{\partial r}\right|_{r=R_o} = h_o \left(T_o - T\right) \tag{3}$$

The heat transfer coefficient at the inside wall, h_i, accounts for conduction and natural convection in the fluid (water) in the bottle. The heat transfer coefficient at the outside wall, h_o, accounts for convection in an air (or water) layer surrounding the bottle and for heat transfer via radiation. We have simplified our analysis by calculating the heat transfer in the radial direction only, assuming insulation boundary conditions at the top and bottom of our cylinders as shown in Figure 1a. This assumption renders our 2-D axially symmetric model to be equivalent to a 1-D model since the temperature will be uniform in the axial direction. We prefer the visual representation of the 2-D model, however, and believe it provides a better physical feel for the problem. For example, it is easier to visualize the area available for heat transfer in 2-D axial symmetry than in 1-D. While not technically precise, with reasonable approximations for heat transfer coefficients, this simple analysis explains the observed trends in our data sufficiently well. To provide a physical interpretation of the heat transfer coefficient, we have also developed models of our bottles that include an equivalent stagnant air or water layer at the outside surface of the bottle. Physical properties used for this layer, the water in the bottles and the ice water bath, and the bottle materials are included in Table 1.

COMSOL Multiphysics finite element software was used to solve Eq. (1) and give a visual representation of the calculated temperature in the bottles as a function of time and position. We also drew the glass and aluminum bottles more accurately as shown in Figure 1b and considered heat transfer through the rubber stoppers and the air above the water in the bottles. We found that modeling results were substantially the same with those geometries as with the equivalent cylinder models.

RESULTS AND DISCUSSION

Cooling a glass bottle in a refrigerator. The solid line in Figure 2 shows the measured temperature as a function of time inside the glass bottle upon cooling in the refrigerator. It took about 8 hours for the beverage to reach the control temperature of the refrigerator (about 1 ˚C). Note that the inflection in the experimental results was always present and appears to be due to the density maximum for water at 4 ˚C.

To understand the heat transfer process, we began by attempting to model it with conduction-only, with the temperature at the outside of the bottle surface fixed at $T_{refrigerator}$ (imagining that there is enough cold air and cooling power

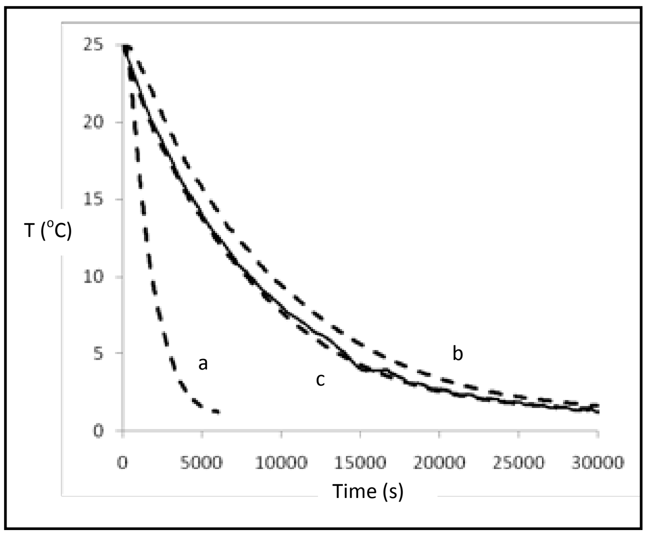


***Figure 2.** Experimental results and model predictions for temperature at the center of a glass bottle upon cooling in a refrigerator. Solid curve, experimental results, Dashed curves: (a) conduction only model with T_o = 1 ℃; (b) outside heat transfer coefficient, h_o = 9 W/m² K, to account for radiation and natural convection in an air layer surrounding the bottle, conduction through stagnant water inside; (c) h_o = 9 W/m² K and h_i = 400 W/m² K to account for natural convection inside the bottle.*

TABLE 2
Outside Heat Transfer Coefficients and Biot Numbers Upon Cooling in Refrigerator and Ice Water

	Cooling in refrigerator		Cooling in ice water	
	h_o (W/m^2K)	Bi	h_o (W/m^2K)	Bi
aluminum	10	0.000024	200	0.00048
glass	9	0.013	200	0.294
plastic	9	0.016	200	0.356

within the refrigerator that the temperature at the bottle surface is constant). That is, we used a constant temperature boundary condition of $T = T_{refrigerator}$ instead of Eq. (3) and considered conduction through water inside the bottle with a continuity boundary condition at the inside wall instead of the boundary condition of Eq. (2). This is clearly incorrect, but some students think this way initially and it is instructive to illustrate the fallacy and correct it incrementally. As shown in curve a of Figure 2, this severely under predicted the time required to come to thermal equilibrium with the refrigerator temperature.

The fixed T boundary condition at the bottle surface is incorrect because the air around the bottle heats up when the warm bottle is placed in the refrigerator. The air some distance away from the bottle will be at $T_{refrigerator}$, but not the air at the bottle surface. It should be clear that introducing a stagnant air layer around the bottle, where T decreases from $T_{surface}$ to $T_{refrigerator}$, would significantly increase the predicted time to reach thermal equilibrium. But how thick should the air layer be? And would it really be stagnant? In reality, density differences brought about by temperature differences in the air near the bottle will result in natural convection-circulation of the air near the bottle. This flow of air near the bottle will result in improved heat transfer over that of a truly stagnant air layer. Complicating matters even further is the fact that heat transfer by thermal radiation provides a significant contribution for objects being cooled in a refrigerator.[11] Rather than deal with all the complexities of this process in detail, Eq. (3) is used as a boundary condition at the bottle surface with the outside heat transfer coefficient, h_o, accounting for contributions from resistance to heat transfer across an outer air layer, natural convection in the air layer, and thermal radiation. By methods described in the Appendix, we estimated h_o to be about 9 W/m^2 K. Using this in the boundary condition of Eq. (3) instead of a constant temperature boundary condition, but still assuming conduction only inside the bottle resulted in curve b of Figure 2.

Natural convection also occurs inside the bottle and is better modeled using the boundary condition of Eq. (2) than by conduction-only with a continuity boundary condition. As explained in the Appendix we estimated the inside heat transfer coefficient, h_i, to be about 400 W/m^2 K and including that along with h_o, as described above, we obtained curve c in good agreement with the experimental data. In this case, the thermal conductivity of the water in the bottle was increased 1000 fold in the model ensuring that all the resistance to heat transfer on the inside of the bottle was lumped into h_i.

Analysis of the results from Figure 2 indicates that the largest resistance to heat transfer is from the air layer surrounding the bottle. The Biot number, defined for this case by,

$$\mathrm{Bi} = \left(h_o t\right) / k \tag{4}$$

gives a measure of the relative importance of convective and conductive heat transfer. A common rule of thumb is that a Biot number less than 0.1 indicates that the thermal resistance due to convection dominates the heat transfer process to the extent that resistance to heat transfer due to conduction is negligible. When applied to the bottle wall, as shown in Table 2, the Biot number for our glass bottle cooling in a refrigerator is small enough that the bottle wall should not affect the process and the wall temperature will be essentially uniform.

This point can be illustrated clearly by modifying our model to include conduction through an equivalent stagnant air layer appended to the outer edge of the bottle wall. Note that air outside the bottle will be in motion due to natural convection, but there will always be a boundary layer near the bottle surface where the dominant heat transfer mechanism is conduction. The thickness, δ_e, of the equivalent stagnant layer (effective thermal resistance layer) that we envision is not necessarily a physically measurable length out from the bottle surface to a point where $T = T_{refrigerator}$, but instead is given as the length required to match the observed heat transfer coefficient,

$$\delta_e = \frac{k}{h_o} \tag{5}$$

Rearranging this equation as $h_o = k / \delta_e$ provides a physical interpretation of the heat transfer coefficient. Considering the thermal conductivity, k, of air as 0.025 W / m K, an effective air thickness of 0.00278 m is required to match our h_o value of 9 W / m^2 K. Including an air layer of this thickness in an equivalent conduction-only model with a fixed $T = T_{refrigerator}$ boundary condition at the outer edge of the air layer reproduced curve b in Figure 2.

To obtain curve c in Figure 2 using our equivalent conduction-only model, we used Eq. (5) to determine that conduction through a thermally resistant water layer with thermal conductivity of 0.6 W / m and thickness of 0.0015 m is equivalent to using h_i = 400 W/m^2 K. It appears that convective mixing inside the bottle results in an effective thermal resistance layer only 1/20th as thick as the bottle inside radius. The rest of the water in the bottle is considered to have a very high thermal conductivity so that it will have uniform temperature and pose no further resistance to heat transfer in this model. An alternative approach that perhaps gives a better feel for the convective mixing going on inside the bottle and provides the same temperature vs. time result (curve c) is to use a moderately high thermal conductivity for all the water in the bottle. An effective thermal conductivity of 12 W/m K (increasing the water thermal conductivity 20 fold) was required for this approach.

The heat transfer rate by conduction through a composite material is given by

$$q = \frac{\Delta T}{\sum R_j} \tag{6}$$

where the resistance to heat transfer due to each material j is given by

$$R_j = \frac{t_j}{k_j A_j} \tag{7}$$

and A_j is the area available for heat transfer into material j. Our equivalent conduction-only model provides a visual representation of the resistance to heat transfer given by the effective outside air layer (representing the outside heat transfer coefficient), glass wall, and the effective inside thermally resistant water layer (representing the inside heat transfer coefficient) as shown in Figure 3a where the predicted temperature is plotted as a function of position in the radial direction for three different times: 60, 600, and 6000 s. It can be seen that the

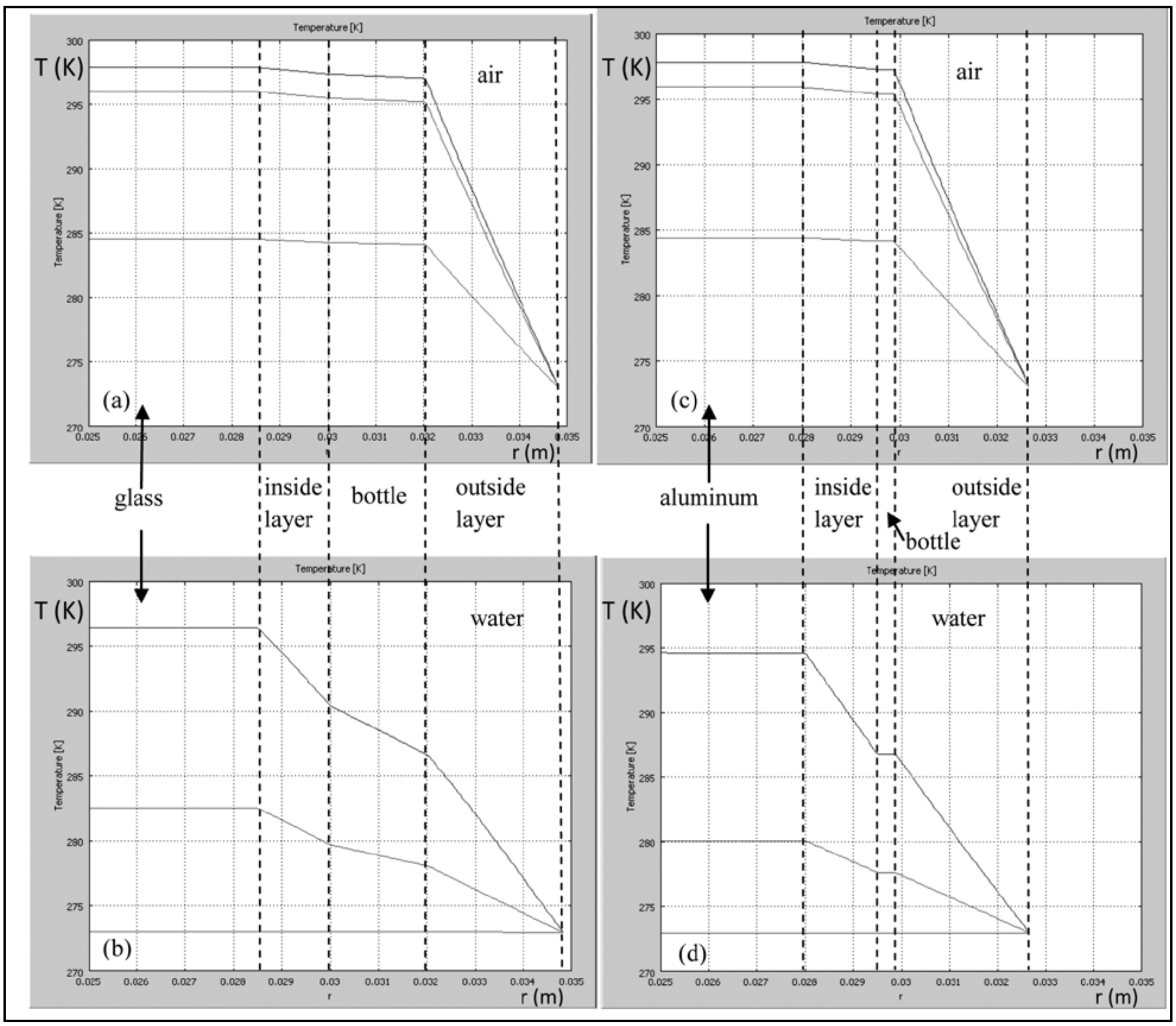


Figure 3. *Predicted temperature profiles in the radial direction for our conduction-only model with effective outside thermal resistance layer of 0.00278 m and effective inside thermal resistance layer of 0.0015 m at three times (60, 600, and 6000 s) for cooling with outside T = 0 ℃ and initial inside T = 25 ℃ for four cases: (a) glass bottle, air outside; (b) glass bottle, water outside; (c) aluminum bottle, air outside; (d) aluminum bottle, water outside. Note that the r-axis begins at r = 0.025 m in these figures.*

effective outside air layer gives the largest resistance (largest temperature drop) and that conduction through the bottle wall has little effect. Note that combining Eqs. (5) and (7) indicates that the resistance outside the bottle equals $1 / (h_o A_o)$. We can also use the built-in post-processing features of COMSOL Multiphysics to evaluate the heat flux across the bottle wall and use Newton's law of cooling,

$$q = h_o A_o \left(T_o - T_a\right) \tag{8}$$

to evaluate the value of h_o represented by the air layer. For example, at 60 s, the heat flow across the outside wall was 7.39985 W and ΔT was approximately 23.35 K. Taking into account the bottle outside surface area of 0.03381 m^2 yields a value of h_o near 9 as expected.

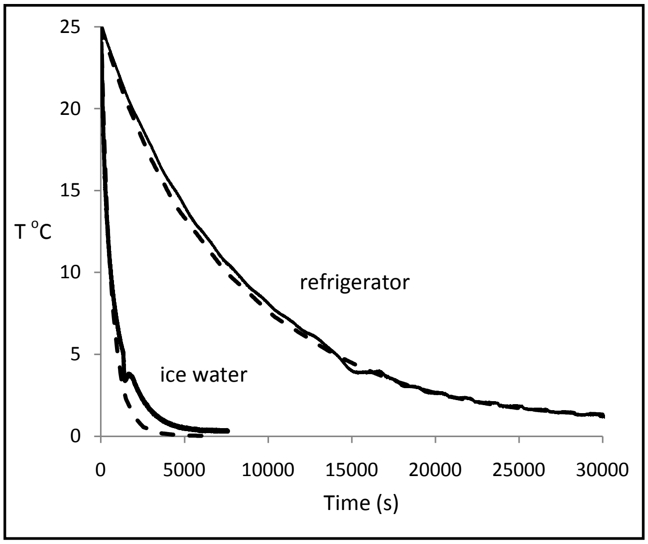


Figure 4. *Comparison of cooling rates for glass bottle in refrigerator or ice water. Solid lines, experimental data. Dashed lines, equivalent stagnant layer conduction models.*

Cooling a glass bottle in ice water. Figure 4 shows the dramatic difference between cooling methods for a glass bottle. An ice water bath is much more efficient than a refrigerator since it takes less than 1.5 hours to make the contents ice cold. The increase in efficiency can be explained as arising mostly from the higher thermal conductivity of water compared to air. Our equivalent conduction-only model was used to illustrate this point by assuming, as an approximation, that a 0.00278 m layer of water rather than air was controlling the heat transfer at the outside of the bottle. Simply using the properties of water instead of those of air in the outer layer of our previous model yielded the predictions shown in Figure 3b and the dashed line of Figure 4. While this does not fit the experimental data exactly, it does show that the difference in thermal conductivity of water and air accounts for most of the difference between the two cooling processes. Comparing Figures 3a and 3b we can see that the resistance to heat transfer offered by the ice water layer is much less than that of the air layer. We can also see that the resistance in the bottle wall is significant in the ice water case. This fact is also reflected in the Biot number since the value for a glass bottle cooling in ice water is no longer less than 0.1 as shown in Table 2. An experienced heat transfer teacher might argue that knowing the Biot numbers is more useful than Figure 3, but we found that Figure 3 clarifies the meaning of the Biot number for the uninitiated.

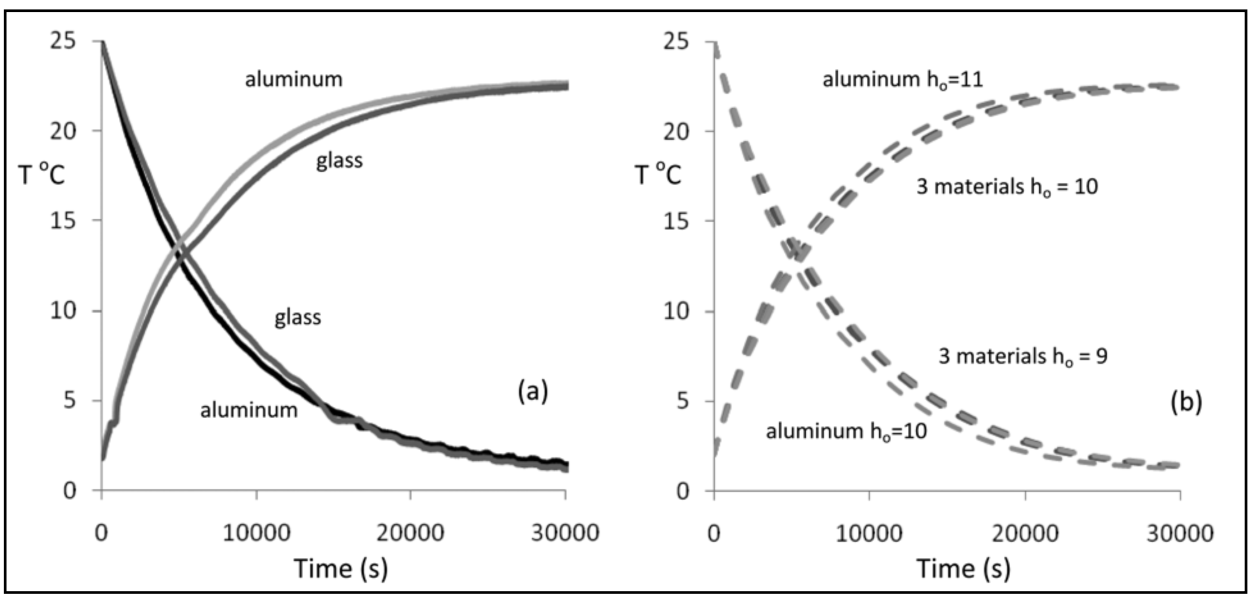


Figure 5. *Comparison of aluminum, glass, and plastic bottles upon cooling in a refrigerator and heating in air. (a) experimental results; (b) predicted results with h_i = 400 W/m^2K, h_o = 9 W/m^2K (10 W/m^2K for aluminum) on cooling and h_o = 10 W/m^2K (11 W/m^2K for aluminum) on heating. Note that experimental results for plastic bottles were nearly identical to those of glass bottles in both situations.*

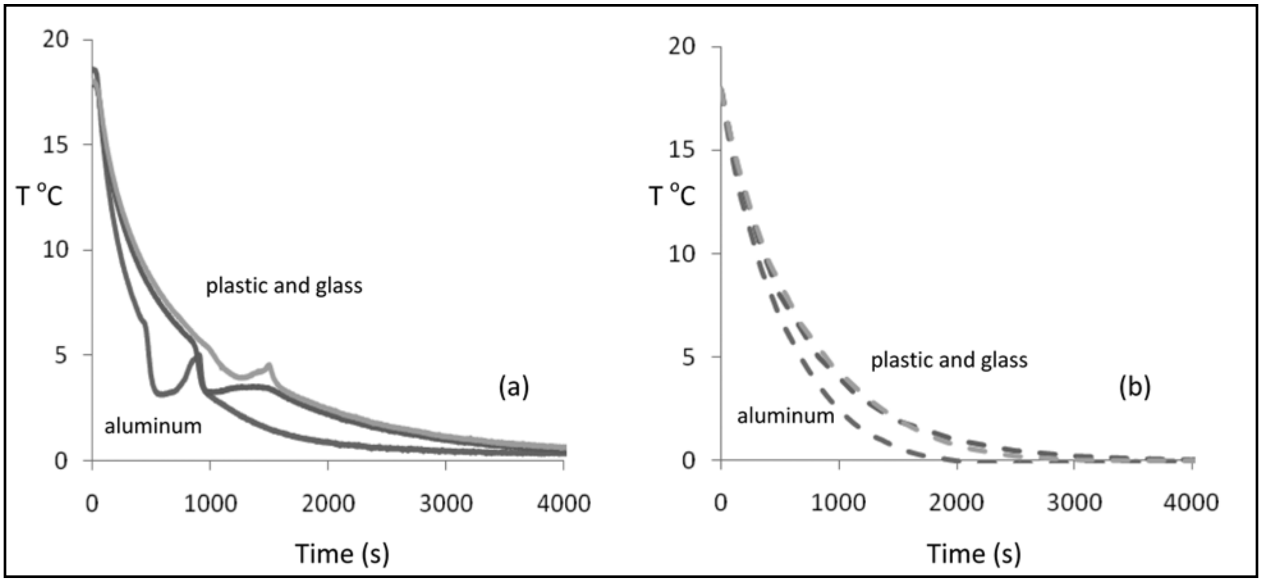


Figure 6. *Comparison of aluminum, glass, and plastic bottles upon cooling in ice water. (a) experimental results; (b) predicted results with h_o = 200 W/m²K, h_i = 400 W/m²K.*

Comparison of various bottle materials. At this point some students might be thinking: "All this theory is fine, but which bottle is better?" The measured and predicted results for cooling in a refrigerator and heating in air are shown in Figure 5. Comparing Figure 3a for glass and Figure 3c for aluminum indicates that the resistance to heat transfer in the air outside of the bottles represented by h_o dominates the process in both cases. Therefore, it is no surprise that Figure 5b shows no significant difference between predicted results if we use the same values of h_i and h_o for all bottles. Our experimental results, in Figure 5a, show that the aluminum bottle always cooled and heated slightly faster than the other two, however. It appears that other factors, like differences in condensation on the bottles and differences in emissivity, that we have not taken into account are needed to explain why the aluminum bottle cools and heats slightly faster. Increasing the values for h_o for the aluminum bottle allowed us to more closely model the observed results. The low Biot numbers in Table 2 for cooling in the refrigerator (and similar results that would be obtained for heating in air) indicate that wall material should have minimal effect on these heat transfer processes.

Experimental and calculated results for cooling the three bottles in ice water are shown in Figure 6. The ice water cooling process appears to be influenced by the density of water maximum at 4 °C and is not accurately modeled with our simple model using constant heat transfer coefficients. Nevertheless, our simple model results, shown in Figure 6b, indicate that the difference in bottle materials does account for some of the observed difference in cooling rates. The resistance to heat transfer illustrated in Figures 3 and the Biot numbers shown in Table 2 help explain why the bottle material has a more significant effect when cooled in ice water than when cooled in air. Figures 3c and 3d show our equivalent resistance-layer conduction-only model results for the aluminum bottle in air and water, respectively. The small thickness and high thermal conductivity of the aluminum bottle yield little resistance to heat transfer (and small Biot number), even when compared with the relatively small resistance offered by the water layer in Figure 3d. The thermal conductivity of plastic is less than that of glass, but the wall thickness of the plastic bottle is also less, resulting in similar thermal properties (and Biot numbers) for the plastic and glass bottles. For glass and plastic, but not for aluminum, the resistance due to the wall does slow down the cooling process in the ice water case.

The fact that the aluminum cools faster will only have practical significance if the process is stopped before equilibrium is reached. The temperature when "the mountains turn blue" is about 6 °C, for example.[12] In ice water, the aluminum bottle will reach that temperature faster than the glass bottle will; how much faster will depend on the starting temperature. For example, for the starting temperature of 18.5 °C, shown in Figure 6, it was about 5 minutes faster, but for a starting temperature of 24 °C (measured but not shown), it was about 8 minutes faster. This advantage for the aluminum bottle is counteracted by the disadvantage that the aluminum bottle heats up significantly faster than the others when hand-held as shown in Figure 7, on the next page (plastic results were similar to those for glass).

To give students a physical feel for the heat transfer process, we found it effective to fill an aluminum bottle and a glass bottle with ice water and have them hold each one. The aluminum bottle feels colder because it conducts heat away from the hand more readily. This explains why aluminum cools faster in ice water and heats faster when hand-held. It might also explain why the myth persists that aluminum keeps beverages colder longer since aluminum feels colder even when the

If time is of the essence, an aluminum bottle in an ice water bath will reach a satisfying temperature several minutes faster than the other bottles due to the high thermal conductivity and thin wall of the aluminum bottle. The aluminum bottle will warm faster than the others when hand-held, but the practical significance of this fact will depend on how rapidly the beverage is consumed. We suspect that the thermal performance of the bottle will not have a major effect on beverage enjoyment, but our studies on this aspect are ongoing.

contents are the same temperature. Having students place their hands next to the two bottles without touching them allows the students to note that the air gap between the hand and the bottle prevents the faster heat transfer to the aluminum that was observed when the hands touched the bottles. Students will also recognize that room-temperature water feels colder than room-temperature air because the water conducts heat away from the body faster.

CONCLUSIONS

The experiments and calculations presented here were both fun and informative. They were an excellent way to reinforce our understanding of heat transfer processes. When cooled in a refrigerator, bottle material has little effect on the cooling rate and about 8 hours is required to cool a 16 oz bottled beverage. We recommend an ice water bath for 1 to 1.5 hours (depending on the starting temperature) if rapid cooling is desired. In this case, plastic and glass bottles behave similarly because the lower thermal conductivity of plastic is offset by a thinner wall. If time is of the essence, an aluminum bottle in an ice water bath will reach a satisfying temperature several minutes faster than the other bottles due to the high thermal conductivity and thin wall of the aluminum bottle. The aluminum bottle will warm faster than the others when hand-held, but the practical significance of this fact will depend on how rapidly the beverage is consumed. We suspect that the thermal performance of the bottle will not have a major effect on beverage enjoyment, but our studies on this aspect are ongoing.

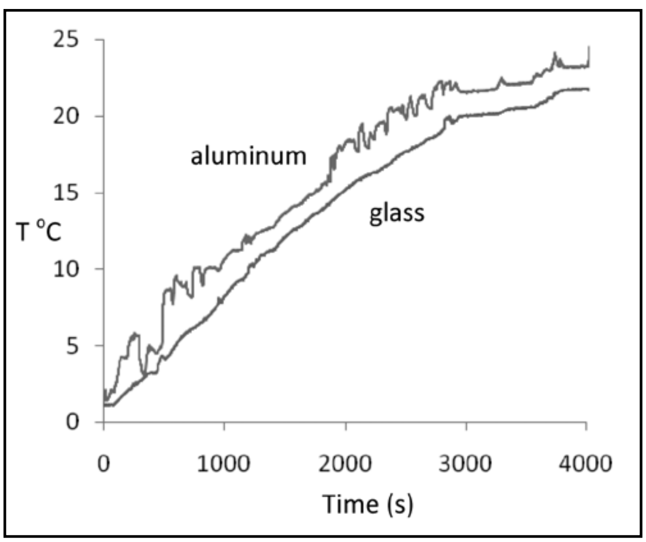


Figure 7. *Hand-held heating experimental results for glass and aluminum bottles.*

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. DUE-0536342. The expertise and help of Jack Ferraro in completing the experimental measurements is also gratefully acknowledged.

REFERENCES

1. "Iron City goes aluminum: Pittsburgh Brewing says metal bottles keep beer colder," (Aug. 25, 2004) <http://www.realbeer.com/news/articles/news-002311.php>
2. "Pittsburgh Brewing and Alcoa Team-Up on Launch of First National Beer in an Aluminum Bottle," (Aug. 24, 2004) <http://www.alcoa.com/global/en/news/news_detail.asp?pageID=242374038&newsYear=2004>
3. "New DANZKA Vodka 'Made to Chill'," <http://www.beststuff.com/print/6465>
4. "Danzka, Made to Chill," <http://www.danzka.com/ready_to_chill.html>
5. "Miller Lite Launches Pint-Size Aluminum Bottle," *Packaging Digest* (11/1/2008) <http://www.packagingdigest.com/article/CA6610053.html>
6. Bryson, L., "Cans or Bottles?," *Massachusetts Beverage Business* (2/2006) <http://www.beveragebusiness.com/archives/article.php?cid=1&eid=12&aid=99>
7. "Beer in PET bottles—alternative packaging," (1/9/2006) <http://www.packaging-gateway.com/features/feature79/>
8. "Miller Rolls Out Plastic Bottles," (3/9/2000) <http://www.realbeer.com/news/articles/news-000738.php>
9. Augustenborg, E.M., "Aluminum vs. Glass... Which Beer Bottle Stays Cooler Longer?", AIChE Annual Meeting, Oct.30-Nov. 4, 2005, Cincinnati, OH, poster 93af, (2005)
10. Bailey, R.T., and W.L. Elban, "Thermal Performance of Aluminum and Glass Beer Bottles," *Heat Transfer Eng*., **29**(7), 643 (2008)
11. Laguerre, O., and D. Flick, "Heat Transfer by Natural Convection in Domestic Refrigerators," *J. Food Eng*., **62**, 79-88 (2004)
12. "Coors Light Loves... Ice Cold Activated," <http://www.coorslight.co.uk/blog/?p=23>
13. Jaluria, Y., *Basics of Natural Convection, in Handbook of Single Phase Convective Heat Transfer*, eds. S. Kakac, R. Shah, and W. Aung, p.12-18, John Wiley and Sons, New York (1987)
14. Hasanuzzaman, M., R. Saidur, and H.H. Masjuki, "Effects of Operating Variables on Heat Transfer and Energy Consumption of a Household Refrigerator-Freezer During Closed-Door Operation," *Energy*, **34**, 196-198 (2009)
15. Raithby, G.D., and K.G.T. Hollands, *Natural Convection, in Handbook of Heat Transfer Fundamentals*, eds. W.M. Rohsenhow, J.P. Hartnett, and E.N. Ganič, pp. 6-67, McGraw-Hill, New York (1987)

APPENDIX: JUSTIFICATION FOR HEAT TRANSFER COEFFICIENTS USED

The heat transfer coefficients in this paper can be considered to be constant average values fit to our experimental results. That is, they are the values that gave the "best" calculated results when inserted into COMSOL Multiphysics as constants in the boundary coefficients defined by Eqs. (2) and (3). In this appendix, standard methods for estimating heat transfer coefficients are used to justify that the fitted values are reasonable and consistent with known correlations. As indicated by the correlations below, heat transfer coefficients are temperature-dependent and will therefore vary with time. Calculations below show the initial values for a glass bottle. Coefficients evaluated for the other bottle materials were similar to those evaluated for glass. Although COMSOL Multiphysics can easily incorporate (and even estimate for you) temperature-dependent heat transfer coefficients, this capability has not been used.

Outside convective heat transfer coefficient – cooling in refrigerator. The heat transfer coefficient describing natural convection at the outer surface of a vertical cylinder can be estimated by[13]

$$h_o = \frac{k}{H}\left[\frac{4}{3}\left[\frac{7\,Gr\,Pr^2}{5\left(20+21\,Pr\right)}\right]^{1/4} + \frac{4\left(272+315\,Pr\right)H}{35\left(64+63\,Pr\right)d_o}\right] \qquad (A1)$$

where

$$Pr = \frac{\nu}{\alpha} \qquad (A2)$$

$$Gr = \frac{Ra}{Pr} \qquad (A3)$$

$$Ra = \frac{g\beta\left(T_s - T_\infty\right)H^3}{\nu\alpha} \qquad (A4)$$

Pr, Gr, and Ra are the Prandlt, Grashof, and Rayleigh numbers, respectively. Using the height, H, and outside diameter, d_o, of the glass bottle given in Table 1, properties for air at T_∞= 1 ˚C given in Table A1, and an initial bottle surface temperature, T_s, of 25 ˚C, the value of h_o given by Eq. (A1) is 4.98 W / m^2 K.

Radiative heat transfer coefficient – cooling in refrigerator. The radiation heat transfer coefficient can be estimated by[14]

$$h_r = \varepsilon\sigma\left(T_\infty + T_s\right)\left[T_\infty^2 + T_s^2\right] \qquad (A5)$$

Using an emissivity, ε, for glass of 0.93 and Boltzmann constant, σ, of 5.67 × 10^{-8} W / (m^2 K^4) yields a value of h_r = 4.94 W / m^2 K.

Combined outside heat transfer coefficient – cooling in refrigerator. Since we have included thermal radiation in our lumped-parameter outside heat transfer coefficient, an estimate of its initial value is h_o = 4.98 + 4.94 = 9.92 W / m^2 K. Since this value will decrease with time an average value of 9 W / m^2 K seems reasonable.

Outside convective heat transfer coefficient – cooling in ice water. Using the values for water at 0 ˚C, given in Table A1 yields an outside heat transfer coefficient for water via Eq. (A1) of h_o = 304 W / m^2 K. The presence of crushed ice in the water near the bottle and the fact that the volume expansivity, β, goes from negative to positive and equals zero at 4 ˚C, caused us to question the accuracy of Eq. (A1) in this situation. With that in mind and realizing that h_o will decrease as T_s decreases indicates that our average value of 200 W / m^2 K is not unreasonable.

Inside heat transfer coefficient. The heat transfer coefficient on the inside of a vertical cylinder can be estimated by[15]

$$h_i = \frac{k}{H}\left[0.55\,Ra^{0.25}\right] \qquad (A6)$$

Using the properties of water at 25 ˚C shown in Table A1, T_∞ = 25 ˚C, and T_s = 1 ˚C in this equation yields h_i = 422 W / m^2 K in agreement with the fitted average value of 400 W / m^2 K that we used. ❒

TABLE A1
Thermophysical Properties for Air at 1 ˚C and Water at 0 and 25 ˚C

	kinematic viscosity $\nu \times 10^6$ m^2/s	thermal diffusivity $\alpha \times 10^6$ m^2/s	volume expansivity $\beta \times 10^3$ 1/K	thermal conductivity k W / (mK)
Air at 1 ˚C	13.357	18.682	3.717	0.023
Water at 0 ˚C	1.795	0.132	- 0.068	0.558
Water at 25 ˚C	0.912	0.146	0.255	0.606

DRUG TRANSPORT AND PHARMACOKINETICS

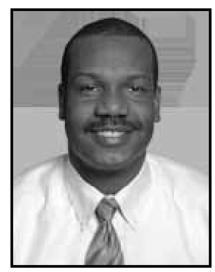
For Chemical Engineers

LAURENT SIMON, KUMUD KANNEGANTI, AND KWANG SEOK KIM

New Jersey Institute of Technology • Newark, NJ 07102

The design and synthesis of a pharmaceutical agent that is able to induce the desired biological effect is a research area that requires expertise outside a regular undergraduate chemical engineering curriculum (*i.e.*, structures and functions of cells, protein, and receptors). Although concepts such as intermolecular forces would sound familiar to a chemical engineering student, a lack of basic understanding of signal transduction pathways would render the task of identifying suitable drug targets insurmountable. Drug delivery using compartmental models, however, is a more accessible option for ChE students with ample training in transport phenomena and especially in solving material balance problems involving single- and multiple-process units. Such perspective is indispensable for a sound understanding of pharmacokinetics, which focuses on drug absorption, distribution, metabolism, and excretion (ADME). In addition to binding properly to receptors and provoking a response, an active pharmaceutical ingredient (API) must be able to reach the target site in sufficient amount.[1] Knowledge of pharmacokinetics is therefore critical in drug discovery and development. For example, the rate of metabolism influences the bioavailability and clearance in humans and preclinical species.[2] This information, combined with the recognition of the enzymes that mediate the metabolism of the specific drug, is paramount at a very early stage in the discovery process. The present work describes a series of laboratory experiments, based on principles of chemical processes, to address questions of clinical relevance. Projects that draw analogies between the approach taken to understand the fate of drugs in the body and the methodology adopted to track materials through an entire chemical plant may offer new insights and opportunities to ChE students.

Engineering educators have already stressed the need to prepare a workforce with knowledge in drug delivery. Several experiments are made available to help students effectively apply principles of chemical engineering fundamentals (*e.g.*, chemical kinetics, mass transfer) to the study of factors influencing drug release from several delivery devices.[3] Cavanagh



***Laurent Simon** is an associate professor of chemical engineering and the associate director of the Pharmaceutical Engineering Program at the New Jersey Institute of Technology. He received his Ph.D. in chemical engineering from Colorado State University in 2001. His research and teaching interests involve modeling, analysis, and control of drug-delivery systems. He is the author of* Laboratory Online*, available at <http://laurentsimon.com/simon/>, a series of educational and interactive modules to enhance engineering knowledge in drug-delivery technologies and underlying engineering principles.*

***Kumud Kanneganti** is pursuing a Master's degree in the Otto H. York Department of Chemical, Biological, and Pharmaceutical Engineering. He received a B. Tech. degree in chemical engineering from Nirma University of Science and Technology (NU), India. His research focus is in the design of drug delivery strategies using well-stirred vessel experiments.*

***Kwang Seok Kim** is a Ph.D. student in the Otto H. York Department of Chemical, Biological, and Pharmaceutical Engineering. He received his B.S. (2004) and M.S. (2006) degrees in chemical engineering from the University of Seoul, Korea. His research interests include the design and control of drug delivery systems.*

and Wagner[4] introduced to engineering students hands-on projects in drug delivery to illustrate flow and pressure through an experimental model of the circulatory system and the concept of drug dissolution. The learning objectives of this contribution are to assist students in i) applying knowledge of mass balances to the design of experiments focusing on the transport of medicaments in the body (*learning objective 1*), and ii) developing a knowledge of multiple IV doses and continuous IV infusion through well-stirred vessel experiments (*learning objective 2*).

The integration of laboratory activities into the study of drug transport and delivery can be beneficial for students majoring in chemical engineering as well as for biomedical engineering undergraduates. A fitting example is a Biotransport course (ChE427/BME427) taught at the New Jersey Institute of Technology. This three-credit class is mandatory for biomedical engineering students pursuing tracks in biomaterials and tissue engineering or biomechanics and is an elective for chemical engineering students. Concepts of transport phenomena, as applied to biological systems, are presented. Examples of topics covered are: body fluids, transcellular solute transport, basics of vectors and tensors, conservation relations, and momentum balances. During the semester, students are expected to develop and present simulation-based projects ranging from pharmacokinetic analysis to hemodialysis. Discussions of the results reveal knowledge of the physics as well as a firm grasp of real-life implications of several design alternatives and treatment regimens.

LABORATORY DESCRIPTION

One-Compartment Model and Multiple IV Dosing Regimens

The one-compartment model offers the simplest way to describe the kinetics of drug absorption and elimination in the body. Based on this representation, the body behaves like a well-stirred vessel (Figure 1).

After a rapid intravenous injection (IV Bolus), the pharmaceutic distributes to rapidly perfused tissues[5] and reaches the systemic circulation instantaneously. In addition, clearance commences immediately after the injection. A mass balance around the process in Figure 1 yields the following differential equation (*learning objective 1*):[5]

$$\frac{dVC_p}{dt} = D\delta(t) - k_{el}VC_p,\ C_p(0) = 0 \tag{1}$$

or

$$\frac{dVC_p}{dt} = -k_{el}VC_p,\ C_p(0) = C_p^0 \tag{2}$$

where D is the loading dose, V is the distribution volume, k_{el} is the first-order elimination rate constant, C_p is the plasma drug concentration at time t, and $\delta(t)$ is the Dirac delta function. The integration Eq. (2) gives:

$$C_p = C_p^0 e^{-k_{el}\times t}. \tag{3}$$

The elimination rate constant can be computed by measuring the slope of the straight line:

$$\ln(C_p) = \ln(C_p^0) - k_{el}\times t. \tag{4}$$

It can be shown that the time required for the plasma drug to drop to one-half of its initial value is:

$$t_{1/2} = \frac{0.693}{k_{el}}. \tag{5}$$

After a single-dose administration, the plasma drug level immediately rises above a minimum effective concentration. If a second dose is not taken at a specific time, however, the medicament may not produce any benefit as the plasma concentration drops well below the therapeutic level. Such a situation can be circumvented by prescribing a multiple-dosing regimen to the patient. This method of administration is not without its own challenge because the impact of each dose on C_p has to be known *a priori* to achieve optimal clinical effectiveness and to minimize deleterious effects. Experiments were conducted to help chemical engineering students understand the influences of key parameters, such as the size of the dose, the administration time, and the elimination time constant on the plasma drug concentration.

Eq. (3) is used to calculate the plasma concentration at the end of the first dosing interval τ:

$$C_{pl}^{r} = C_p^0 e^{-k_{el}\times\tau} \tag{6}$$

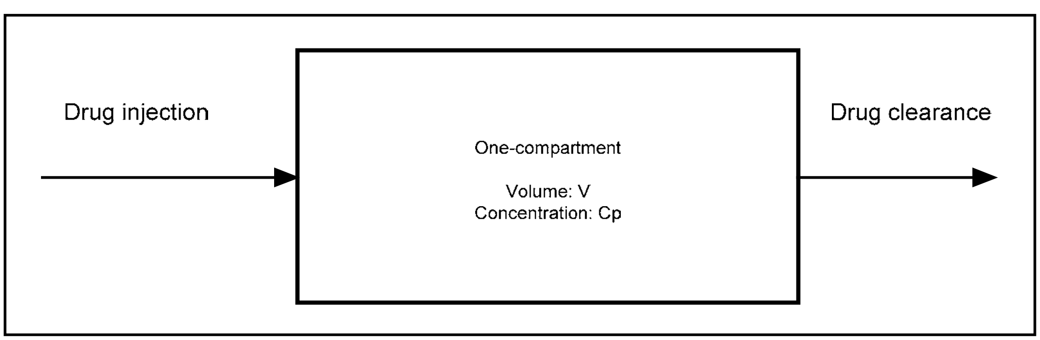


***Figure 1.** Representation of a one-compartment model.*

where C_p^0 is the loading dose. It can be shown that the concentration within the nth interval is:[1]

$$C_{pn}\left(t\right)=C_p^0\left(\frac{1-e^{-n\times k_{el}\times\tau}}{1-e^{-k_{el}\times\tau}}\right)e^{-k_{el}\times t}. \tag{7}$$

At steady-state (*i.e.*, $n\to\infty$), the minimum and maximum C_p values are:

$$C_{p\,min\,ss}=C_p^0\left(\frac{1}{1-e^{-k_{el}\times\tau}}\right)e^{-k_{el}\times\tau}. \tag{8}$$

and

$$C_{p\,max\,ss}=C_p^0\left(\frac{1}{1-e^{-k_{el}\times\tau}}\right), \tag{9}$$

respectively. The principle of superposition assumes that early doses of the medicament do not influence the pharmacokinetics of the subsequent doses.

Materials and Experimental Procedure

The materials used in the experiments were: variable flow-rate pumps, 250-mL, 200-mL, and 4-L beakers, stopwatch, 10-mL graduate cylinders, pipettes, rubber tubes, magnetic stirrer, magnetic bars, potassium permanganate, spectrophotometer, cuvettes, laboratory stands, and clamps. The apparatus is shown in Figure 2. The beaker with the $KMnO_4$ solution was placed on a magnetic stirrer. A pump was used to mimic drug clearance from the body (*i.e.*, waste pump). Water was introduced at a rate similar to that of the waste pump in order to maintain a constant volume of liquid in the central compartment. The rubber tubes were fastened firmly with clamps (Figure 2).

Two main parameters were adjusted in developing a dosage regime: the size of the dose and the administration frequency. The study demonstrated why the drug strength and dosing interval are important for treatment. After initially adding 10 ml of $KMnO_4$ to the beaker, a new dose was added every 30 or 45 seconds. Samples were collected at regular 15-second intervals and analyzed with the spectrophotometer. The dose sizes were 0.0003657 g/mL and 0.000547 g/mL. In general, the ease with which samples are collected and the objective of a particular study determine the sampling interval. In this investigation, it was necessary to collect samples at a relatively fast rate to obtain a full picture of the system dynamics because of the short duration of each experiment. For the multiple IV bolus study, a new dose was added every 45 seconds. As a result, a sampling period of 15 seconds would allow a student to record the concentration before and after the addition of a new dose. A sample size of 1.3 mL was selected so that a constant volume was maintained in a 200/250 mL beaker. A larger dose would violate the constant volume assumption made in deriving the equations and, therefore, affect the analyses. The stirring rate was set sufficiently high to allow mixing to occur and low enough so that the formation of eddies did not influence the elimination rate causing inaccurate results.

Results and Discussions

In practice, each drug has a therapeutic range in the human body. A medicament administered should not exceed the minimum toxic concentration (MTC) or fall below the minimum effective concentration (MEC). The maximum and minimum plasma concentrations should be kept within this window. Figure 3 shows that the dose strengths have a strong impact on $C_{p\,min\,ss}$ and $C_{p\,max\,ss}$ (*learning objective 2*). As a laboratory project, students can be asked to design drug-dosage regimens based on information regarding $C_{p\,min\,ss}$ and $C_{p\,max\,ss}$. Other hands-on activities may focus on investigating whether the number of doses required to reach a steady state is a function the dose size. Other worthwhile pursuits are to use

Figure 2. *The experimental setup.*

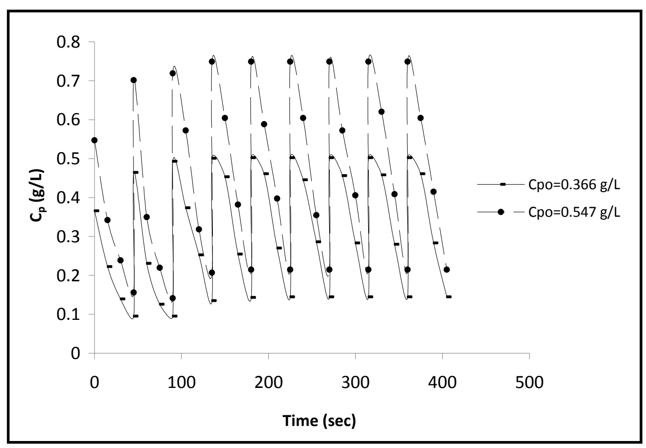


Figure 3. *Concentration of $KMnO_4$ in the central compartment using nine IV boluses and two separate drug sizes: k_{el} = 0.028 sec^{-1}, and τ = 45 sec, C_p^0 = 0.366 g/L (regimen 1) and C_p^0 = 0.547 g/L (regimen 2).*

the governing equations to predict the experimental profiles or to comment on the effect of drug clearance on the fate of the drug in the body.

Bolus Doses Followed By a Constant-Rate Infusion

Drugs are administered intravenously in the form of a bolus dose or infused relatively slowly through a vein into the plasma at a constant or zero-order rate. One of the main advantages of an IV infusion is that an effective constant plasma drug concentration can be achieved, thereby eliminating the fluctuations observed in bolus IV dosing. Also, since the injected bolus dose takes 5 to 15 minutes to be completely diluted in the bloodstream,[1] a slow infusion is preferred, in some cases, to prevent an adverse effect caused by a high plasma drug concentration.

Eq. (1) is modified to account for the constant rate of infusion (k_0 in unit of mass/time) (*learning objective 1*):

$$\frac{dVC_p}{dt} = k_0 - k_{el}VC_p \tag{10}$$

For a constant volume and $C_p(0)=0$, the solution is:

$$C_p\left(t\right) = \frac{k_0}{k_{el}V}\left(1 - e^{-k_{el}\times t}\right). \tag{11}$$

The steady-state concentration:

$$C_{pss} = \frac{k_0}{k_{el}V} \tag{12}$$

is essentially achieved when $t=5\times t_{1/2}$. One of the consequences of this relationship is that medicaments with long half-lives take a long time to reach a desired steady-state level (or to be within a known therapeutic range). As a result, one of the strategies often used is to first administer bolus doses until the drug level is in a prescribed range. A continuous infusion ensues immediately to maintain an effective constant plasma concentration (*learning objective 2*).

Eq. (7) is first applied to calculate the plasma concentration during the multiple-dosing phase. Note that the value at the end of the last period N is given by:

$$C_{pN}\left(\tau\right) = C_p^0\left(\frac{1 - e^{-N\times k_{el}\times\tau}}{1 - e^{-k_{el}\times\tau}}\right)e^{-k_{el}\times\tau} \tag{13}$$

where τ is the dosing interval. The solution to Eq. (10) with the initial condition defined by Eq. (13) gives the equation for the constant-infusion period:

$$C_p\left(t\right) = \frac{k_0}{k_{el}V} + \left(C_{pN}\left(\tau\right) - \frac{k_0}{k_{el}V}\right)e^{-k_{el}\times t} \tag{14}$$

Materials and Experimental Procedure

The volume of liquid in the central compartment was kept at 200 mL. In one set of experiments, four boluses of $KMnO_4$ were administered at one-hour intervals followed by a constant-rate infusion. Operating conditions and kinetics obtained in a constant-rate infusion study were applicable in this case (*i.e.*, k_{el}=0.014 min^{-1},C_{pss}=2.0 g/mL, k_0=5.6 g/min). Samples of $KMnO_4$ solution were collected from the central compartment every 15 minutes until the concentration reached the steady-state value. Results of this investigation were compared to a different dosage regimen where two boluses were used prior to the continuous infusion.

Results and Discussions

The concentration profiles for the two and four IV boluses with infusion are displayed in Figure 4. One key advantage of the multiple doses plus the infusion is a distribution of the total amount of injected medicament during the therapy.[6] The increase in the dimension of the input space, however, makes it difficult to develop the best drug-dosing strategy.

Several researchers have worked on such problems and proposed several algorithms to address the issue. Students should be given the opportunity to estimate the best injection times, drug dose sizes, and infusion rates. The sum of squared errors for the two and four boluses plus infusion are 0.306 and 0.576, respectively.

SUMMARY OF EXPERIENCES

The educational objectives are formulated to fit courses, or programs, that provide an introduction to pharmacokinetics and drug transport. For example, in the case of IV bolus injections, not only do students need to understand that the blood concentration decreases faster for drugs with a shorter half-life but also why this process is important to patient compliance and administration protocols. Based on feedback and oral testimonies from students of ChE427/BME427, simulations—based on first-principle modeling—have been demonstrated to foster a better understanding of graduate courses in pharmaceutical engineering and some aspects of

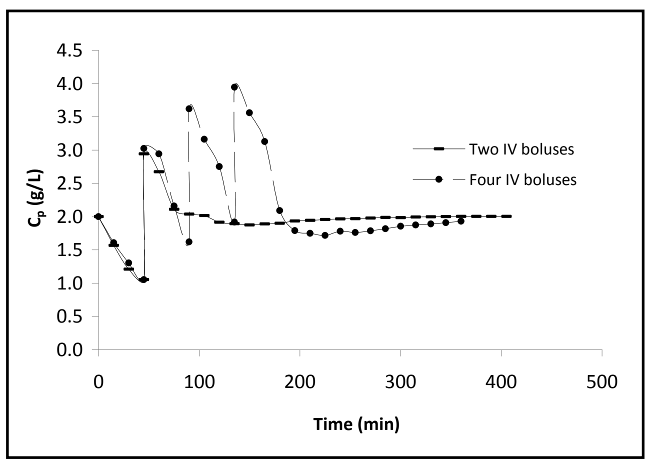


Figure 4. *Concentration of $KMnO_4$ in the central compartment for two and four IV boluses followed by a constant-rate infusion of k_0 = 5.6 k g/min.*

current drug-delivery practices. In Spring 2009, three out of five projects were based on pharmacokinetics and dosing regimens. One group of students investigated the effects of drug half-life and multiple-dosing regimens on the maximum and minimum plasma drug concentrations. Another assignment focused on the impact of pharmacokinetic parameters on drug concentrations in the central and peripheral compartments of a two-compartment model. Simulations were also conducted to address several aspects of a continuous drug infusion (*e.g.*, time to achieve steady-state). The students from this group welcomed the idea of incorporating laboratory data from the constant rate-infusion experiment into their projects. Because of time constraints and the fact that some of the laboratory materials/experiments were not available at the time, students' requests for conducting multiple-dosing experiments were not met. Nevertheless, the entire class attended a demonstration in the laboratory on IV bolus experiments using well-stirred vessels. Initial responses indicated that the transition from simulation-based to experimental projects (*learning objective 2*) would be well-received.

CONCLUSIONS

Several experiments were proposed to help chemical engineering students understand pharmacokinetic processes using familiar continuous-stirred vessels. In line with the educational objective of applying knowledge of fundamental physical principles (*learning objective 1*), these activities made extensive use of curriculum topics, such as mass balance equations and process dynamics, in an attempt to build on existing knowledge and to reinforce concepts taught in the classroom. Concentration-time profiles of potassium permanganate were monitored in a one-compartment stirred-tank model for single and multiple IV boluses. The influences of dose strengths and administration periods were investigated. The constant-rate infusion, although preferable to bolus injections for some medicaments, presents its own challenges, *e.g.*, the plasma drug concentration takes a long time to reach a steady-state. Experiments were designed to enable students to use their knowledge of process dynamics in developing drug-dosage regimens that meet certain criteria. Combined with multiple boluses, a continuous infusion may be appropriate for a series of drugs and treatments (*learning objective 2*). Designed laboratory activities would allow students to appreciate the benefits and overcome difficulties of this particular protocol. After participating in a demonstration of IV bolus injections, students, who worked on simulation-based projects in drug transport, were very supportive of the addition of a laboratory component to the Biotransport course.

REFERENCES

1. Schoenwald, R.D., *Pharmacokinetic Principles of Dosing Adjustments*, CRC Press, Boca Raton (2001)
2. Gunaratna, C., "Drug Metabolism and Pharmacokinetics in Drug Discovery: A Primer for Bioanalytical Chemists, Part I," *Curr. Sep.*, **19**(1), 17 (2000)
3. Farrell, S., and R.P. Hesketh, "An Introduction to Drug Delivery for Chemical Engineers," *Chem. Eng. Ed.*, **36**(3), 198 (2002)
4. Cavanagh, D.P., and J.J. Wagner, "A Three-Week Hands-On Introduction to Biotransport and Drug Delivery for First-Year Engineering Students," *Proceedings* of the 2004 American Society for Engineering Education Annual Conference and Exposition, Session 1309 (2004)
5. Truskey, G.A., F. Yuan, and D.F. Katz, *Transport Phenomena in Biological Systems*, 2nd Ed., Pearson Prentice Hall, Upper Saddle River, NJ (2009)
6. Kim, K.S., and L. Simon, "Optimal Intravenous Bolus-Infusion Drug Dosage Regimen Based on Two-Compartment Pharmacokinetic Models," *Comput. Chem. Eng.*, **33**(6), 1212 (2009) ❒

INTRODUCING DECISION MAKING UNDER UNCERTAINTY AND STRATEGIC CONSIDERATIONS IN ENGINEERING DESIGN

Georgia Kosmopoulou, Chintamani Jog, Margaret Freeman, and Dimitrios V. Papavassiliou
The University of Oklahoma • Norman, OK 73019

The material that is commonly taught in chemical engineering design for engineering economics could be described as "risk free," in the sense that the economic estimations presented to students appear to be free of financial uncertainty. The teaching of concepts in economics is usually focused on the treatment of the time value of money (*i.e.*, interest and inflation), the calculation of deterministic values for profitability criteria (*e.g.*, return on investment, net present worth), and the calculation of equipment cost and plant cost. Uncertainty is usually associated with limitations of the engineering models used to estimate the cost of the major pieces of equipment in the plant. For example, the students are taught that the models used to calculate the heat transfer area for a heat exchanger are based on semi-empirical correlations and, thus, the estimated cost of a heat exchanger might be inaccurate. The uncertainty about raw material and product prices, about the cost of energy and about labor cost, and the fact that the actual values might depend on factors that are outside of an engineer's control (*e.g.*, weather, natural disasters, international financial landscape) is not usually emphasized.

In fact, not only most textbooks in chemical engineering design but also most textbooks on engineering economics used within other engineering disciplines offer the same "risk free" content. Concepts such as cost estimation and profitability are, of course, quite important for quantifying the economic feasibility of an engineering project, but the availability of models that can handle financial risk, uncertainty, and decision making calls for an update of the instruction material. Recently, some effort has been placed on the introduction of risk analysis in chemical engineering design.[1] Uncertainty as well as other important concepts such as decision tree analysis and utility functions, however, have not been part of a typical undergraduate curriculum.

Lately, through collaboration between the University of Oklahoma Department of Chemical Engineering and Department of Economics, we have developed classroom games that demonstrate concepts such as strategic decision making, the winner's curse, and the utility function in Design I—a course that introduces engineering economics to chemical engineers who lack an extensive economics background. In this paper, we discuss the development of these games (or class experiments, as they would be called in the economics literature) and the educational objectives of each game. We also demonstrate the basic components of these games and we discuss the mechanics of carrying out experiments in the classroom. The concepts that are visited with the games can be used to quantify risk and facilitate decision making under uncertainty.

TAKING FINANCIAL UNCERTAINTY INTO ACCOUNT

Uncertainty and change are pervasive in the careers of new engineers, and mastering appropriate analysis techniques and tools will be greatly beneficial to graduates. A rather easy concept for the students to grasp is the incorporation of uncertainty in the decision-making process by maximizing expected profits. A good example for introducing expected profit to students is the drilling of an oil well (this is an example offered in detail as a case study in the textbook by Mansfield[2]) or the rolling

***Georgia Kosmopoulou** is the Edith Kinney Gaylord Presidential Professor at the Department of Economics at the University of Oklahoma. She received a B.S. from the University of Piraeus and her M.S. and Ph.D. from the University of Illinois at Urbana-Champaign. Her research interests are in industrial organization, auction theory, and mechanism design.*

***Chintamani Jog** is a Ph.D. student in the Department of Economics at the University of Oklahoma. He received his B.A. degree in economics from the University of Mumbai and M.A. in economics from Gokhale Institute of Politics and Economics, Pune.*

***Margaret Freeman** is a junior in chemical engineering at the University of Oklahoma. She is also pursuing a minor in entrepreneurship for engineering majors and is the recipient of an NSF-REU fellowship at Oklahoma.*

***Dimitrios Papavassiliou** is a Presidential Professor at the School of Chemical, Biological, and Materials Engineering at the University of Oklahoma. He received a Diploma from the Aristotle University of Thessaloniki, and M.S. and Ph.D. degrees from the University of Illinois at Urbana-Champaign. His research interests are in turbulent transport, transport in porous media, microfluidics, and computational transport. He has been teaching Design I during the past 10 years.*

out of a new product line. A company cannot be sure in advance whether it should be done and what the costs are going to be. Based on the best expert opinion that a company has, a probability density function can be obtained with discrete outcomes associated with possible profit. The expected profit is then given as

$$E(\pi) = \sum_{i=1}^{N} P_i \pi_i \tag{1}$$

where N is the number of possible outcomes, P_i is the probability that outcome i will occur, and π_i is the profit for outcome i.

In the examples that follow, the choice of the values of the discrete probability function was made arbitrarily. In practice, however, one cannot generate the probability density function in a rigorous statistical manner, since one cannot be placed in the same business conditions and be faced with the same decision possibilities repeatedly. A particular business situation usually occurs once, thus, one cannot generate a sample of outcomes given the decisions made. The probability density function is usually generated after brainstorming and after consulting with experts having prior experience in similar situations. In the case of rolling out a new product one needs to use market analysis and surveys, in the case of pricing raw materials and products one needs to use forecasting techniques, and in the case of drilling a well one needs to rely on the opinion of geologists and geophysicists who are experienced in the interpretation of geological data (such as data obtained through seismic analysis or core analysis).

Example 1: Assume that if a new product (say raspberry-flavored Cola) is produced, there will be a 40% likelihood that it will not catch up in the market, 25% probability that it will get 1% of the competitors' market share, 20% probability that it will get 2% of that market, and 15% probability of a 3% additional market share. If the product is not rolled out, there will be no profit. Figure 1 is a decision tree presenting the payoffs arising from choices made by the decision maker and by chance outcomes. The expected profit from no change in the product line is zero while the expected profit from the introduction of a new product is

$$E(\pi) = 0.4(-20{,}000) + 0.25(50{,}000) + 0.20(100{,}000)$$
$$+0.15(150{,}000) = \$47{,}000.$$

If one makes decisions trying to maximize expected profit, then one should clearly decide to produce the new product, since the expected profit from that decision is higher than the expected profit from no change in production.

An example like this introduces students to a methodology for taking uncertainty into account, and provides the opportunity to discuss decision tree analysis (see Reference 2, or any other managerial economics textbook, for more on decision trees). The discussion of expected profit, however, also leads to the opportunity to discuss the utility functions as a way to quantify uncertainty and a way to incorporate the attitude of the decision maker towards risk. This discussion can start in the classroom by considering a case where the expected profit of two options is about the same, but one of the two is much more risky.

Example 2: A company can invest in a process that can yield a net present worth (NPW) of \$1,000,000 with no risk, and a process that can have either a NPW of \$2,150,000 with probability of 50% or a negative NPW of -\$50,000 with a 50% probability. The expected NPW for the risky option is \$1,050,000. Which option would the students pick?

In this example, the criterion of maximizing expected NPW in order to account for uncertainty conflicts with common sense. The students can see that there might be a company that cannot afford a 50% probability of losing \$50,000, especially if this is a small company that could go out of business! The utility function can be used to quantify the attitude towards risk and to justify a decision that is clearly not based on expected profit maximization. But, what *is* a utility function?

It is a function that places a numerical value on happiness, or more specifically on the willingness to buy different goods or take different actions for companies and consumers! On Sept. 6, 2007, the student newspaper at the University of Oklahoma campus (*The Oklahoma Daily*) ran a half-page article entitled "Happiness Has a Personal Side" with pictures of 10 students and their responses to the question "What makes you happy?" Chocolate, shopping, family, and penguins were among the responses—answers that make good sense to students in the Design class. This article illustrated very nicely that happiness (and the utility function that attempts to quantify it) is subjective, and it was quite effective as a handout for relating the concept of the utility function to each student. A utility function has to be ordinal as it is difficult to quantify differences in happiness from different decisions and actions. The ordinal character of a utility allows people

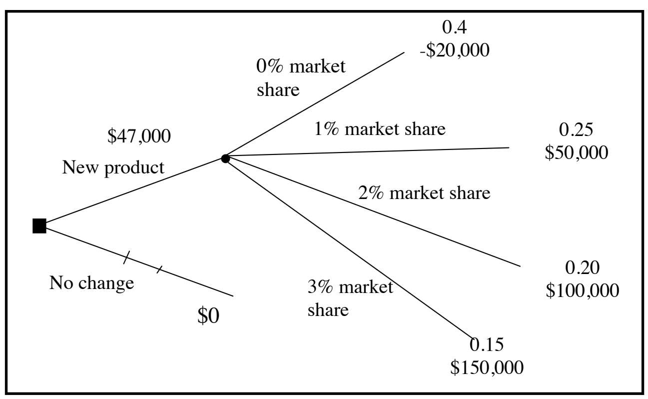


***Figure 1**. Decision tree that graphically depicts the probable outcomes of rolling out a new product. The probability of each outcome is shown on the decision tree, as well as the profit or loss if the outcome occurs. The dollar value that appears on each branch is the expected profit that corresponds to the branch.*

to express their preferences between the no-risk option and the risky option in Example 2 and be consistent in choosing different courses of action.

How can a utility function be constructed? First, one can assign arbitrary values to the extremes of the possible profits.[2] For example, using the numbers offered in Example 1, we can say that the utility function has a value of zero for a loss of $20,000 and the value of 100 for a profit of $150,000. Any two arbitrarily chosen numbers would work, so long as the value of the utility function for the minimum profit is smaller than the value of the utility for the maximum profit. The value of the utility function at any intermediate profit π between the two extreme values π_{min} and π_{max} is found by determining the probability P for which the decision maker is indifferent between a risky option that includes the extremes and a safe option with profit π. In particular:

$$U(\pi) = P\,U(\pi_{min}) + (1-P)\,U(\pi_{max}) \qquad (2)$$

In other words, the person whose utility function is generated in this exercise is equally happy to take a safe bet with a return equal to π and a gamble with probability P of a return π_{min} and probability (1- P) of a return π_{max}. In this respect, the decision on whether to commit to one financial option or another can be based on *maximizing the expected utility*, calculated as

$$E(U) = \sum_{i=1}^{N} P_i\,U(\pi_i) \qquad (3)$$

where $U(\pi_i)$ is the value of the utility function for profit π_i.

To demonstrate to the students the utility function concept and to illustrate how a utility function can be generated, we have prepared a game that can be played by the students in class.

<u>Game 1:</u> The game presents students with a series of two options, one of which is a gamble and the other a safe choice. In Figure 2, we are trying to determine the utility of

GAME 1

You need to make a series of choices between Options 1 and 2 and record your choices in the spreadsheet before rolling a fair 10-sided die. Consider your payoffs as the sum of the payoffs from each choice.

You need to choose between a "safe" bet, which is Option 2, and a "gamble" that can result in either a loss of $20,000 or a win of $150,000, based on the dice-rolling outcomes, which is Option 1.

• 1st choice:

<u>Option 1:</u> If the die comes up 1, you win $150,000, but if it comes up 2,3,..., 10 you lose 20,000.

<u>Option 2:</u> You win $0 no matter what the dice-rolling outcome is.

Make your choice between these two options and record your choice by typing 1 or 2 in the appropriate cell in the column titled "Record choice (1 or 2)" (column D in your Excel Sheet).

• 2nd choice

<u>Option 1:</u> If the die comes up 1, 2, you win $150,000, but if it comes up 3,..., 10 you lose 20,000.

<u>Option 2:</u> You win $0 no matter what the dice-rolling outcome is.

Again make your choice between these two options and record it by typing 1 or 2 in the appropriate cell in the column titled "Record choice (1 or 2)."

Continue up to the tenth choice having in mind that as you go down the list the probability of a favorable outcome in Option 1 increases by 1/10.

• Record the dice rolls in the column titled "Record dice roll (1-10)."

	B	C	D	E
1			Record choice	Record dice
2	Option 1	Option 2	(1 or 2)	roll (1-10)
3	Roll 1 to win $150,000, roll 2-10 to lose $20,000	0		
4	Roll 1,2 to win $150,000, roll 3-10 to lose $20,000	0		
5	Roll 1-3 to win $150,000, roll 4-10 to lose $20,000	0		
6	Roll 1-4 to win $150,000, roll 5-10 to lose $20,000	0		
7	Roll 1-5 to win $150,000, roll 6-10 to lose $20,000	0		
8	Roll 1-6 to win $150,000, roll 7-10 to lose $20,000	0		
9	Roll 1-7 to win $150,000, roll 8-10 to lose $20,000	0		
10	Roll 1-8 to win $150,000, roll 9,10 to lose $20,000	0		
11	Roll 1-9 to win $150,000, roll 10 to lose $20,000	0		
12	Any roll wins $150,000	0		
13				
14			Actual sum of return	
15			Expected sum of return	
16				
17				
18				

Game 1 | Game 2 | Game 3 | Game 4 | Game 5 | Utility Function | Retu

Figure 2. *Example of the game that students play in order to determine the value of the utility function of a profit equal to zero (Option 2). Option 1 is a gamble between the two extreme values of the profit, taken from Example 2, with different probability of winning or losing, and thus different expected utility. The expected utility at which the player switches from the safe option to the gamble is the point of indifference and indicates the value of U(0).*

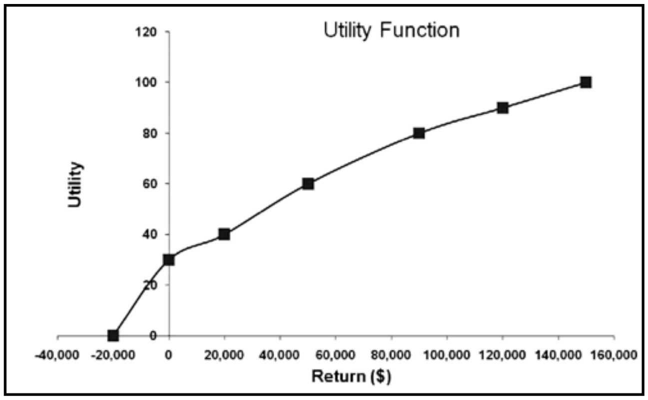


Figure 3. *Typical utility function resulting from Game 1. This is the utility function of a risk-averse person, since the value of the utility increases at decreasing rate as the expected return increases.*

zero profit by offering a set of choices between U(0) and a gamble between U(150,000) and U(-20,000). The players are asked to select their options and to input their selection in the spreadsheet.

The game is constructed using Microsoft Excel, which allows the instructor to lock certain cells of the spreadsheet and to pre-arrange the figures to present the data from specific parts of the spreadsheet. Student players cannot input numbers in places that can alter the structure of the game. The students play this game five times for five different safe profit values. When the game ends, each student's utility function for this example has been constructed, and some of the students can e-mail their spreadsheets to the instructor or place their utility function on a memory stick and show it to the rest of the class. At that point a discussion in class can be initiated on whether the person whose utility function is shown is a "risk-loving" or a "risk-averse" person. In addition, another discussion can be initiated based on the question of what the utility of a different amount than those chosen for the five games might be. Figure 3 is a typical outcome for the utility function from this game.

Having created the utility function, the students can return to Example 1 and apply the maximization of expected utility as a decision criterion. They can calculate the expected utility of rolling out a new product, compare it with that of not changing the production line, and make a choice. This will give students an immediate application of the concepts learned. More importantly, it becomes evident that this approach is bound to give different answers for different people, since it is the utility and not the profit that is maximized. Different attitudes towards risk are not captured by mere expected profit maximization, but they are taken into account when expected utility is maximized.

ATTITUDE TOWARDS RISK

The second classroom game builds on the first one. It is intended to be an application of the risk preferences seen earlier, introducing the ideas of "actual" and "expected" values.

GAME 2

Due to the EPA's concern over rising levels of greenhouse gasses, all chemical companies are required to reduce CO_2 emission by 15%. For the past few years, Independent Chemical, Inc., has subcontracted another company to process CO_2. The cost keeps rising, however, and Independent Chemical, Inc., is considering handling the CO_2 capturing in-house. Your consulting company is hired by Independent Chemicals, Inc. They want you to suggest which of the following technology options for CO_2 sequestration they should use:

Option 1: Build a bio-energy carbon storage plant next to their existing facility to capture and store CO_2.

Option 2: Use gas hydrate technology to transport CO_2 and store it in ocean.

Problem: Both technologies are not well tested, so there is no certain estimate of the profits, and if there are technical issues that will arise with the new processes, there might even be fines from the EPA.

Game Guidelines

• You need to make a choice between Options 1 and 2 and record your choice in the spreadsheet before rolling a fair 10-sided die that determines the outcome.

You need to choose between Option 1, which even in the case of failure can make money, and Option 2, which, in the case of failure, will result in a loss of $500,000.

• 1st choice:

Option 1: If the die comes up 1, you win $2,000,000, but if it comes up 2,3,..., 10 you win $1,000,000.
Option 2: If the die comes up 1, you win $3,850,000, but if it comes up 2,3,..., 10 you lose $500,000.

Make your choice between these two options and record your choice by typing 1 or 2 in the appropriate cell in the column titled "Record choice (1 or 2)" (column D in your Excel Sheet).

• Continue making choices up to the tenth set of options having in mind that as you go down the list the probability of the most favorable outcome in both options increases by 1/10.

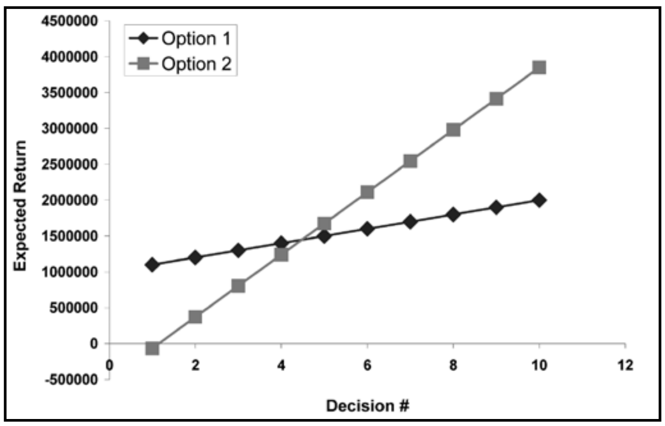
Game 2: The game presents students with a series of two options, each one with different expected profit and different level of risk. This game is also constructed using Microsoft Excel so that spreadsheet cells can be locked and figures can be generated based on the responses of the students. Figure 4 is a snapshot of the excel spreadsheet at the beginning of the game.

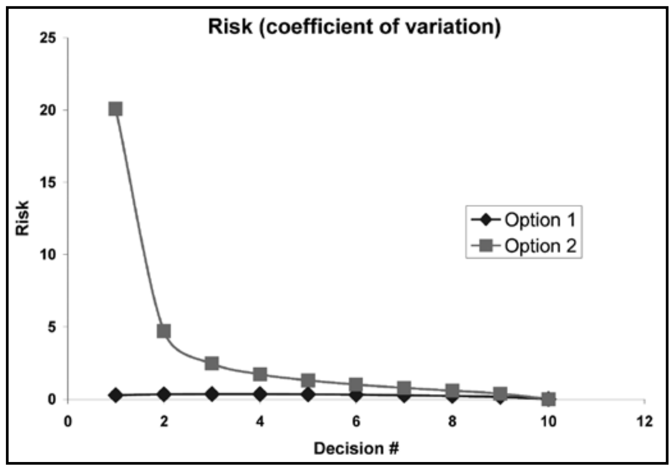
The expected return for each of the options in the game is different. Figure 5a is a plot of the expected profit for both of

Option 1	Option 2	Record choice (1 or 2)	Record dice roll (1-10)
Roll 1 to win $2 mil, roll 2-10 to win $1 mil	Roll 1 to win $3.85 mil, roll 2-10 to lose $0.5 mil		
Roll 1,2 to win $2 mil, roll 3-10 to win $1 mil	Roll 1,2 to win $3.85 mil, roll 3-10 to lose $0.5 mil		
Roll 1-3 to win $2 mil, roll 4-10 to win $1 mil	Roll 1-3 to win $3.85 mil, roll 4-10 to lose $0.5 mil		
Roll 1-4 to win $2 mil, roll 5-10 to win $1 mil	Roll 1-4 to win $3.85 mil, roll 5-10 to lose $0.5 mil		
Roll 1-5 to win $2 mil, roll 6-10 to win $1 mil	Roll 1-5 to win $3.85 mil, roll 6-10 to lose $0.5 mil		
Roll 1-6 to win $2 mil, roll 7-10 to win $1 mil	Roll 1-6 to win $3.85 mil, roll 7-10 to lose $0.5 mil		
Roll 1-7 to win $2 mil, roll 8-10 to win $1 mil	Roll 1-7 to win $3.85 mil, roll 8-10 to lose $0.5 mil		
Roll 1-8 to win $2 mil, roll 9,10 to win $1 mil	Roll 1-8 to win $3.85 mil, roll 9,10 to lose $0.5 mil		
Roll 1-9 to win $2 mil, roll 10 to win $1 mil	Roll 1-9 to win $3.85 mil, roll 9,10 to lose $0.5 mil		
Any roll wins $2 million	Any roll wins $3,850,000		
		Actual sum of return	
		Expected sum of return	

Return / Risk / Decision / Sheet2 / Sheet3

Figure 4. *Example of the game that students play in order to determine their attitude towards risk. Option 1 is a gamble that has a smaller risk, but it also has a smaller expected profit beyond the fifth row.*





Figures 5. *(a, left) Expected profit for options in Game 3; (b, right) corresponding estimate of risk for options in Game 3. The risk is always higher for Option 2, while the expected profit of Option 1 is higher for Option 1 until the fourth choice.*

the game options. One can clearly see that the expected return for Option 2 becomes higher than that for Option 1 after the fourth choice. As one can see in Figure 5b, however, the risk is higher for Option 2 every single time, until the tenth choice. Figure 5b is a plot of the risk for each game option expressed as the coefficient of variation (*i.e.*, the standard deviation normalized by the expected value).

If one were taking into account only expected returns, they should be choosing Option 1 for the first, second, third, and fourth choices, and then switch to Option 2. If one is risk-averse, they would stay with Option 1 even after the fourth choice, preferring to have a lower expected value but assuming a lower risk. The spreadsheet also allows the students to generate a figure called "Your decision," where they can see a plot of the expected value of the return for their choices and of the actual return as a result of the dice rolls. The thick solid line traces the choices made, and can indicate whether the player is risk-loving, risk-averse, or risk-neutral.

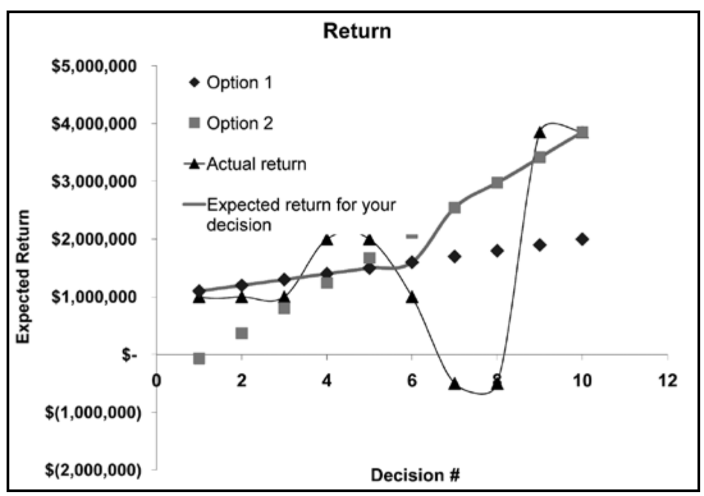


Figure 6. *Typical outcome of Game 3. The thick solid line indicates the expected profit based on the options chosen by this player. This is a risk-averse person, who chooses a lower expected profit with smaller risk. The triangles indicate the actual return based on the outcome of the particular dice roll.*

At the conclusion of the game, some of the students e-mail their "decision" figure to the instructor, in order to show it to the rest of the class (as in Figure 6, previous page). A discussion about whether this would be a curve characteristic of a "risk-loving" or a "risk-averse" person can be initiated. A risk-neutral person would try to maximize expected payoff as their only objective. Hence, the switch from Option 1 to Option 2 would occur at the fifth decision. Thus, for a potential risk lover, the switch should occur before the fifth decision and for a potential risk averter, same should be true beyond the fifth choice. The best part of this experiment is that students can see it for themselves merely by observing each other's diagrams and the decisions made.

DECISION MAKING IN COMPETITIVE SITUATIONS AND WINNER'S CURSE

In business, a strategic decision-making process is characterized by the firm's actions and counteractions leading to payoffs that vary with the outcome of the interaction process. Besides having uncertainty about the outcome of a process, there is also uncertainty about how the competitors will behave. The strategic interactions among competing firms can lead to changes in the production level that affect the technical and economic functions of a company. A simple game that can illustrate this concept, and is quite easy to do in class, is the following:

Game 3: The students are asked to write on a piece of paper a number between 0 and 100. The winner is the person who writes down the number that is going to be closer to 2/3 of the average of the number that everyone in class writes.

To win in this game one must consider what the rest of the class is going to do and act accordingly. The game is rather easily handled in a classroom situation. Three or four students in the class collect the papers from the students sitting close to them, and they add the numbers on the papers they collect in order to expedite the procedure of calculating the class average. We have played this game with the seniors for several years, and almost every time the winner is a person who writes a number close to 23. The winner is asked to explain their way of thinking, as are other students in the class. Everybody who pays attention in the class understands that if the numbers were written randomly, the average would have been 50. The winner usually thinks that 2/3 of 50 is 33, and thus, since almost everybody, the thinking continues, will write down a number close to 33, one needs to pick 2/3 of 33. That would be a number close to 22 or maybe a little higher than 22, in order to account for those who randomly write numbers without thinking through the problem. It is interesting, and contrary to economic theory, that the winner does not continue the thought process to assume that the rest of the class will reach the same conclusion. If that were the case, one would win if he or she would write down a number that is close to 2/3 of 22. If everybody thought this way, then one needs to pick 2/3 of that number, and after several iterations of this type of thinking, the "equilibrium point" according to economic theory is to pick the value of zero!

The goal of this experiment is to use a game theoretical approach to demonstrate to students how to better understand strategic decisions. A major point that can be made by the outcome of this game is that the decision should be made after considering what the other players are going to do and that the winner is the one who guesses how many iteration levels the competitors will consider.

This game serves as a good introduction to the problem of the winner's curse arising in common value auctions, which is relevant to engineers when, for example, they compete for design projects or for raw materials. In such cases, the value of the items is common but unknown during the bidding process (*e.g.*, bidding for exploration and production rights in a plot that one does not exactly know the quantity of oil and gas reserves). The winner's curse was first discussed by Capen, et al.,[3] a group of petroleum geologists who described the bidding outcome in offshore oil lease sales for the period 1954-1969. Studying the bids and profits of the companies participating in the auctions during this period, they observed that, "in a competitive oil and gas lease sale, or indeed in any bidding situation in which the ultimate value of the object to be won is subject to uncertainty, the highest bidder is the one who has overvalued the prize." In that sense, the winner is the most optimistic bidder, who is systematically overbidding (and losing money on average). This phenomenon was termed the winner's curse. It was caused by the failure of the bidders to use the optimal bidding strategy. The optimal bidding strategy should have taken into account what winning implies about the estimates of the competing firms. The winner's curse affected the ability of firms in the oil and gas industry to compete profitably in oil-lease sales and it is a phenomenon nested within many other applications (engineering contracts, etc.). More importantly, it is a wonderful way to explore with engineering students a very practical case where strategic decision making is crucial, and where methodologies now exist that can optimize a firm's behavior under uncertainty.

PRACTICAL ISSUES AND STUDENT FEEDBACK

The games presented here can be played either during a 1-hour and 15-minute class period or over two 45-minute class periods. We have used Games 1 and 2 in a class of participants in a workshop for Experimental Economics held at the University of William and Mary in May 2009, in a Master's-level graduate class of Managerial Economics in August 2009, and in a class of chemical engineering seniors in October 2009. In all cases, the spreadsheets were not available to the students long before the game, in order to avoid biased behavior. For the chemical engineers, the Excel files were e-mailed to the class about five minutes before class time.

The dice rolls can be done by digital means, either generating random numbers in Excel or using a dice-rolling website (*e.g.*, <http://www.random.org/dice/>). In fact, the chemical engineering seniors were so anxious to get to the dice rolls that they were using their own dice-rolling software on their laptops.

The feedback from the players included some ideas to make the games more fun or more relevant. Instead of making all the choices and then dice rolling 10 times, they suggested that dice rolling should follow after each one choice was made. In a larger class of about 45 students, however, it is not practical to go though this process. It was also suggested to adjust the value of the profits offered in the games to make them more relevant to the average student's income, instead of having profits on the order of millions or hundreds of thousands. Another suggestion was to reward the students according to their winnings, either with class credit or with monetary awards. One would expect that such a change in the format of the game, where the players would have a personal stake in the outcome, would lead to risk-averse behavior, which is consistent with economic theory. The goal of the games, however, is not to explore how the players react to different situations, but to illustrate to the players the concepts of risk and decision making under risk.

The response to an anonymous survey of whether participation in the games improved understanding of the utility function and of what is meant by attitude towards risk was that the games were helpful and that they should be incorporated in the class material for Design I. The spreadsheets, as well as the directions for conducting the games, are available to interested colleagues who might want to use them in their classes. The values of the options in the games can be changed according to the goals of each instructor.

CONCLUDING DISCUSSION

The advantage of running experiments in class, in addition to engaging students in active learning, is the ability to control external factors that may be affecting decision making as they change (*e.g.*, risk, uncertainty). Resources for designing other economics experiments are available on the web, for example through the Veconlab software developed by C. Holt at the University of Virginia[4] or through the EconPort portal developed by J. Cox, et al., at Georgia State University.[5]

Modern developments in economics and management include tools and techniques that address uncertainty, risk, strategic thinking, and decision making in a systematic and quantitative way. Deterministic models for the calculation of net present worth, for example, should be used to introduce the concept, but further analysis that incorporates financial uncertainty should be offered. The value of risk can be estimated with techniques like those presented by O'Donnell, et al.[1] The calculated risk can be used in conjunction with utility functions, such as those presented in the present work, to adjust the calculated NPW according to the methodology presented by Mansfield,[2] where the cash flows are substituted by their certainty equivalent values.

ACKNOWLEDGMENTS

The support of the National Science Foundation through a Course, Curriculum, and Laboratory Improvement grant (NSF-0737182) is gratefully acknowledged. An earlier version of this work has been presented at the AIChE meeting in Nashville in November 2009.

REFERENCES

1. O'Donnell, B.R., M.A. Hickner, and B.A. Barna, "Economic Risk Analysis, Using Analytical and Monte Carlo Techniques," *Chem. Eng. Ed.*, **36**(2), 94, (2002)
2. Mansfield, E., *Managerial Economics*, 4th Ed., W.W. Norton & Company Inc., New York (1999)
3. Capen, E.C., R.V. Clapp, and W.M. Campbell, "Competitive Bidding in High-Risk Situations," *J. Petrol. Tech.*, **23**, 641 (1971)
4. C. Holt, "Webgames and Strategic Behavior: Recipe for Interactive Learning," 2002, also: <http://veconlab.econ.virginia.edu/admin.htm>
5. Cox, J.C., and J.T. Swarthout, Georgia State University, EconPort web page, <http://www.econport.org/econport> ❐

VERSATILE DESKTOP EXPERIMENT MODULE (DEMo) ON HEAT TRANSFER

Adrienne R. Minerick*
Michigan Technological University • Houghton, MI 49931

The junior-level Heat Transfer class is the first course in conduction in 1-D and 2-D systems (Cartesian, cylindrical, and spherical coordinates); conduction through composite walls; evaluation of resistances; heat transfer enhancement using fins; convective heat transfer (laminar and turbulent flow, flow past immersed bodies and tube banks); overall heat transfer coefficient; and heat exchanger design. The current text for this course is Incropera and DeWitt's *Fundamentals of Heat and Mass Transfer*.[1] It should be noted that this work was first presented and published in the 2009 ASEE conference proceedings as paper # AC 2009-1609.[2]

The main course objective is to provide junior-level undergraduate students with fundamental knowledge of heat transfer in chemical engineering processes and process equipment. Special emphasis is given to the economics of heat exchanger design and heat recovery.

It is assumed that students entering the class are proficient in:

- *Manipulating units in their solitary form or with Δchanges such as ΔT,*
- *Performing mass and energy balances,*
- *Drawing flow profiles and calculating flow in rectangular and cylindrical geometries, and*
- *Physically interpreting a derivative and solving linear ordinary differential equations.*

Throughout the course, students learn and demonstrate the tools, skills, and knowledge to:

- *Distinguish between and apply mathematical models for the three mechanisms of heat flow (conduction, convection, and radiation).*
- *Draw temperature profiles and describe heat flow given system geometry, medium, and direction of temperature gradients.*
- *Calculate rates of heat transfer and analyze data to determine heat flow in various geometries, in media, and in common heat exchangers.*
- *Identity types of heat exchangers, evaluate heat transfer efficiencies, and size and select heat exchangers for specific applications.*

Desktop Experiment Modules (DEMos) can augment understanding at multiple points in the Heat Transfer course. They are versatile, inexpensive, and portable experiments positioned on student desks throughout a classroom. They are superior to instructor-led demonstrations because:

1) each student can closely examine and manipulate the apparatus,

2) student teams can progress through experiment discovery at their own learning pace, and

3) all learning styles are stimulated to maximize understanding of important fundamental concepts.

The DEMo approach has been successfully implemented with two previous DEMo experiments in an Introduction to Chemical Engineering course. The experiments were Charged Up on Electrophoresis and Brewing with Bioreactors, and were disseminated via ASEE *Proceedings* publications and a website resource.[3-5] Other chemical engineering programs have adopted these experiments.[6] Since these hands-on ex-

***Adrienne Minerick** is an associate professor of chemical engineering at Michigan Technological University, having recently moved from Mississippi State University where she was a tenured associate professor. She received her Ph.D. and M.S. from the University of Notre Dame and B.S. from Michigan Tech. At MTU, Adrienne has taught graduate kinetics. At MSU, she taught the graduate Chemical Engineering Math, Process Controls, Introduction to Chemical Engineering Freshman Seminar, Heat Transfer, and Analytical Microdevice Technology courses. Her research is in medical microdevice diagnostics and dielectrophoresis.*

* *Work conducted at: Mississippi State University, Mississippi State, MS 39762*

periences do not require dedicated lab space, students have a simple yet unique experience to link into their evolving understanding of chemical engineering principles. As a result, these learning tools also serve as vibrant, hands-on experiments with high school students.

This latest Desktop Experiment Module focuses on demonstrating heat transfer concepts. The DEMo is versatile so that it can be incorporated into any existing chemical engineering Heat Transfer course as either a quick, illustrative example during a traditional lecture or as a mini experiment to demonstrate conduction through various materials or convection. While there is latitude in the equipment purchased for these DEMos, if an IR surface thermometer is purchased, it serves as an illustrative example of radiative heat transfer as well.

Advantages of this hands-on experience include that it is not dependent on the availability of lab space and that students have a unique experience to link into their evolving understanding of chemical engineering heat transfer concepts. An instructor can chose to focus on one or more of the following topics when they adapt this experiment: 1-D steady-state conduction, composite systems, contact resistance, thermal energy generation, heat diffusion equation and boundary conditions, fins, convective heat transfer, and many other applications. Coupling the demonstrations with exercise problems in which students must look up properties, assess thicknesses of materials, etc., also adds practical grounding to homework assignments. Course materials including a supply list, example exercises, and experimental procedures are discussed and are available for instructor use via a website.[5]

DESKTOP EXPERIMENT MODULE

A supply list is provided first such that the materials referenced below are familiar to the reader.

Supplies and Setting Up

These supplies will need to be ordered some time in advance. Total cost for 10 stations is about $650.

For each team of students (~2 students per team):

- *Coffee cup warmer [any brand is fine, but avoid high edges around the hot plate. Mr. Coffee brand is ~$10]*
- *CPU passive heat sink with fan [example is Thermaltake P4 Spark II CPU Cooler for Socket 478 (Item #: 6634928, Mfr. Part#: A1584) ~$7]*
- *CPU passive heat sink without a fan (no forced convection) [Example is Northbridge Chipset Passive Heat Sink (Item #: 7037826, Mfr. Part#: ZM- NB32K) ~$3]*
- *Silicone-base heat sink compound [RadioShack has this or Dow sometimes offers samples, ~$3]*
- *Rods of aluminum, copper, steel [1.5 inches in diameter, cut to 1 inch sections, Example is Speedy Metals Online, <www.speedymetals.com>]*
- *Blocks of wood, Styrofoam, glass, drywall [cut to the same size, 3" square, can obtain from hardware store]*
- *Fisher Brand infrared thermometer [Cat #15 077 966, resolution is 0.1°C, accuracy ±1°C]*
- *9 volt batteries*
- *9 volt battery adaptor [obtain from RadioShack]*

For the classroom (or laboratory):

- *Extension cords with power strips*
- *Paper towels for wiping up heat sink compound*
- *Extra batteries*

1-Dimensional Conduction:

Heat transfer is illustrated through use of a coffee cup warmer plate and surface IR thermometer. By examining the warmer as a heat source on a wall of a material, 1-D conduction can be quickly illustrated on each student's desk. Thermal conductivity of different materials can be demonstrated as well. Problems can be set up in which the students have to back calculate to determine the thermal conductivity of the material from the two surface temperatures and distance information. Further, composite systems can be examined via wood, Styrofoam, and drywall sandwich blocks.

The choice of materials is such that it spans a wide range of thermal conductivities as demonstrated in Table 1.[1, 7]

<u>Experimental Procedure:</u>

1. *Turn on mug warmer with the block of material positioned on top and allow the system to heat up for 15 minutes.*
2. *Check the temperature at the top surface of the material three times at 30-second intervals to ensure the system has reached steady-state.*
3. *Check the temperature at the surface of the mug warmer once the system has reached steady-state. Note that this may be greater than the steady-state temperature of the mug warmer when exposed only to convection in the air.*
4. *Replace with new blocks of material allowing it to equilibrate between temperature readings.*

TABLE 1
Suggested Materials and Their Thermal Conductivities

Material	Thermal Conductivity $\left(\frac{W}{m \cdot K}\right)$
Polystyrene (R-12)	0.027
Softwood (Fir)	0.12
Plaster board	0.17
Polycarbonate	0.21
Firebrick	1.0
High Density Carbon Steel	60.5
Aluminum Alloy 2024	177
Copper	401

Analysis:

The heat diffusion equation for 1-D, steady-state conduction with constant thermal conductivity is as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)=0 \Rightarrow \frac{\partial^2 T}{\partial x^2}=0 \quad (1)$$

The general solution is as follows:

$$T(x)=C_1 x + C_2 \quad (2)$$

Boundary conditions are determined from the student's experiment. The following example uses data for a polycarbonate block 1 cm thick. Polycarbonate was chosen because its glass transition temperature is about 150 ˚C and therefore it won't soften or melt on the mug warmer surface.

$$T(0)=T_{w.s} \Rightarrow T(0)=122\,^{o}C \quad (3)$$

$$T(L)=T_{p.s} \Rightarrow T(0.01m)=88.8\,^{o}C \quad (4)$$

The particular solution is in symbolic and numeric form:

$$T(x)=\frac{T_{p,s}-T_{w,s}}{L}x+T_{w,s}$$

$$T_{polycarb}(x)=\left(-3320\frac{^{o}C}{m}\right)x+122\,^{o}C \quad (5)$$

Students will obtain a different temperature profile for each material they study and can then use Fourier's Law to determine the conduction heat transfer flux.

$$q_x^{"}=-k\frac{dT}{dx}=\frac{k}{L}\left(T_{w,s}-T_{p,s}\right) \quad (6)$$

By providing the thermal conductivity, k, or the heat flux, $q_x^{"}$, it is possible to calculate the other parameter. Alternatively, students could determine heat flux from the steady-state heat generation experiment outlined below.

$$q_x^{"}=\frac{0.21\frac{W}{m\cdot k}}{0.01m}\left(122^{o}C-88.8\,^{o}C\right)=697\frac{W}{m^2} \quad (7)$$

1-Dimensional Conduction Through Composite Systems

Steady-state heat conduction through layers of materials can be accomplished as well by stacking the materials provided in Table 1. The analysis is similar to that outlined above.

1-Dimensional Conduction with Contact Resistance

Contact resistance can be demonstrated by using a high thermal conductivity fluid in between the mug warmer and the material block from Table 1. A silicone-base heat sink compound is easy to obtain and, when used, it can be assumed to represent "perfect contact" between the warmer surface and the material block. Comparison with the system outlined above (which has air in the gap between the warmer and the material block) enables the student to back out the resistance due to thermal contact resistance. With access to wood or the metals with a rough edge from cutting vs. a smooth edge after cutting, this can also be illustrated.

$$q_{x,compound}^{"}=\frac{0.21\frac{W}{m\cdot k}}{0.01m}\left(122\,^{o}C-93.1\,^{o}C\right)=607\frac{W}{m^2} \quad (8)$$

Obtaining the total thermal contact resistance for the case with and the case without heat sink compound is:

$$R_{t,c}^{"}=\frac{122\,^{o}C-88.8\,^{o}C}{697\frac{W}{m^2}}=0.04763\frac{^{o}C\cdot m^2}{W} \quad (9a)$$

$$R_{t,c,compound}^{"}=\frac{122\,^{o}C-93.1\,^{o}C}{6o7\frac{W}{m^2}}=0.04761\frac{^{o}C\cdot m^2}{W} \quad (9b)$$

$$R_{t,c}^{"}-R_{t,c,compound}^{"}= \quad (10)$$

$$0.04763\frac{^{o}C\cdot m^2}{W}-0.04761\frac{^{o}C\cdot m^2}{W}=2.15*10^{-5}\frac{^{o}C\cdot m^2}{W}$$

As demonstrated, in this case of a smooth polymer surface, thermal contact resistance can be neglected as it is a couple of order of magnitudes smaller than the thermal resistance associated with the material. Rough metal blocks are good illustrators of how poor physical contact between two materials can impede flow of thermal energy.

Heat Generation Analysis

Heat generation can be considered by expanding the system boundaries to include the electrical resistance heating in the plate warmer. Solution of the heat diffusion equation with constant flux from an electrical heater can be explored via either transient heat generation or steady-state heat generation.

Transient Heat Generation

The transient nature of electrical resistance heat generation can be illustrated by simply having the students measure the temperature of the plate warmer with the IR thermometer from when it is turned on until it reaches steady-state. A sample experimental procedure is given and data is provided in Figure 1 for two experiments. If students are too hasty in ending the experiment, they may miss reaching the true steady-state temperature, which in this case is approximately 122 ˚C.

Experimental Procedure:

1. *Take initial temperature reading of plate warmer before turned on and record its initial temperature at time 0.*
2. *Turn on the plate warmer and begin stopwatch at the same time.*
3. *At 15-second intervals, take a temperature reading of the plate warmer using the infrared thermometer. Make sure to measure at the same location for each reading.*

4. *Continue to take readings until the mug warmer temperature is constant for 45 seconds and reaches steady-state.*

Analysis:

The spatial variations in temperature are not considered in this case, so the heat diffusion equation is just:

$$\dot{q} = \rho C_p \frac{dT}{dt} \tag{11}$$

Assuming that heat generation, $\dot{q}$, is constant, the solution to this differential equation is:

$$T(t) = \frac{\dot{q}}{\rho C_p} t + C_1 \tag{12}$$

Using the initial condition that the temperature of the mug warmer was initially at 22.3 °C, it is possible to solve for the constant of integration.

$$T(t)0 = 22.3\,^{o}C = 0 + C_1 \Rightarrow C_1 = 22.3\,^{o}C \tag{13}$$

Therefore the particular temperature distribution expression is as follows and can be compared to the data fitted by a linear trend line with a fixed y-intercept of the initial mug warmer temperature.

$$T(t) = \frac{\dot{q}}{\rho C_p} t + 22.3\,^{o}C \Leftrightarrow T(t) = \left(0.2646 \frac{^{o}C}{s}\right) t + 22.3\,^{o}C \tag{14}$$

By taking apart one of the mug warmers, it can be ascertained that the plate is primarily aluminum, which has a density of $\rho = 2702 \frac{kg}{m^3}$ and a heat capacity of $C_p = 903 \frac{J}{kg \cdot K}$. Heat generation can then be obtained:

$$\dot{q} = 646{,}000 \frac{W}{m^3} \tag{15}$$

It can be valuable to discuss with students the case in which, when constant power is supplied to the mug warmer and this translates into constant heat generation from the mug warmer, why the data is curved. Most students will deduce that convection from the surface is being neglected and that this contribution only gets greater as the temperature increases.

Steady-State Heat Generation

It is possible to determine the steady-state heat generation by performing an energy balance at the surface of the mug warmer. The students will need to consider that all heat generated by the plate is being convected away from the mug warmer and will also need to obtain a valid convective heat transfer coefficient for convection from the surface of the mug warmer.

Since heat generation is usually expressed as a volumetric generation rate $\left(W/_{m^3}\right)$, it is important to pay attention to units. Further, electrical heat generation can be estimated via Joule heating in the mug warmer's heating coil, which has an electrical resistance, R_e, and a current, I. So

$$\dot{q} = \frac{I^2 R_e}{V} \text{ and } q'' = \dot{q}L [=] \frac{W}{m^2} \tag{16}$$

Energy Balance at the Mug Warmer Surface:

Energy generated in the plate = energy convected away from plate

$$\dot{q}L = h\left(T_{w,s} - T_{ambient}\right) \tag{17}$$

While convective heat transfer coefficients can be determined more rigorously, for this exercise, it is fine to use $h = 5 \frac{W}{m^2 \cdot K}$. The thickness of the mug warmer's heating coil has to be assumed from the thickness of the unit in use, but L=0.01m is realistic. The students can easily measure the ambient air temperature, and the surface temperature of the mug warmer at steady-state was already obtained. Therefore:

$$\dot{q} = \frac{h\left(T_{w,s} - T_{ambient}\right)}{L} = \frac{5 \frac{W}{m^2 \cdot K}\left(122\,^{o}C - 22\,^{o}C\right)}{0.01m} = 50{,}000 \frac{W}{m^3} \tag{18}$$

Heat flux is then:

$$q'' = \dot{q}L = 50{,}000 \frac{W}{m^3} \cdot 0.01m = 500 \frac{W}{m^2} \tag{19}$$

Using the well-known electrical relation for Power, P:

$$P = V \cdot I [=] \text{Volts} \cdot \text{Amperes} [=] \frac{J}{C} \cdot \frac{C}{s} = \text{Watts} \tag{20}$$

The current can be calculated from the information typically provided on the mug warmer unit.

$$I = \frac{P}{V_{AC}} = \frac{17W}{120V_{AC}} = 0.142A \tag{21}$$

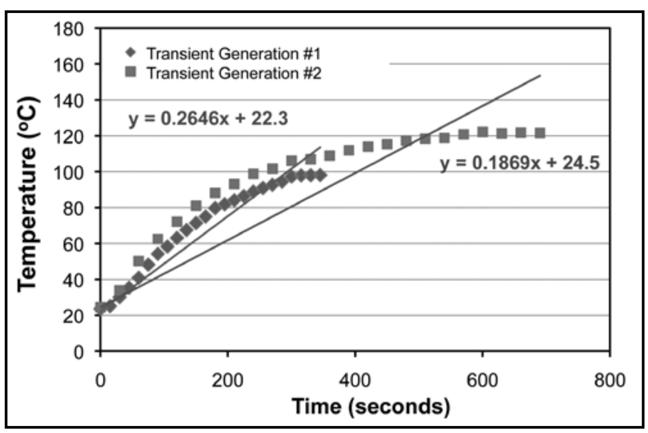


Figure 1. *Transient heating of the mug warmer demonstrating transient heat generation.*

And the electrical resistance can then be obtained through the volume, v, of the warmer plate:

$$\dot{q} = \frac{I^2 R_e}{v} = 50{,}000\frac{W}{m^3} = \frac{\left(0.142\frac{C}{s}\right)^2 R_e}{0.01m \cdot \pi \cdot (0.045m)^2} \quad (22)$$

$$R_e = 158\frac{J \cdot s}{C^2} = 158\Omega \quad (23)$$

Thermal Contact Resistance

Thermal contact resistance can also be illustrated using a coffee mug on the plate warmer. By adding an empty cup at room temperature to the fully heated plate warmer, the students can observe the transient heating of the cup. If transient heating has already been covered, however, it is possible to have the student set up the experiment and then conduct lecture or other class activities until the system reaches steady-state. This typically takes about 15 minutes.

<u>Experimental Procedure:</u>

1. *Allow the plate warmer to heat up and reach steady-state (about 15 minutes to T_{ss}≈120 ˚C).*
2. *Measure initial temperature of the empty mug inside the cup pointing the IR thermometer at the bottom center surface.*
3. *Place the coffee cup on the mug warmer and start the stopwatch.*
4. *At 15-second intervals, record the temperature of the bottom inside surface of the mug.*
5. *Continue to take readings until the mug warmer temperature is constant for 45 seconds and reaches steady-state.*

<u>Analysis:</u>

Since two thermal resistances exist between the surface of the mug warmer and the bottom surface of the coffee cup, it is not possible to isolate the thermal contact resistance from the ceramic mug's resistance. It can be a valuable exercise, however, to ask students to determine from tables the thermal conductivity (and thus calculate thermal resistance) of the coffee mug itself. Depending on whether fired clay or rock is chosen, the thermal conductivity is usually between 1.3 and 2.15 W/mK.[1] Estimating the thickness of the bottom of the cup to be 0.5 cm, the thermal resistance of the cup can be determined to be (per unit area):

$$\frac{L}{k} = \frac{0.05m}{1.7\,W/mK} = 0.029 m^2K/W \quad (24)$$

Using the heat transfer rate obtained from the steady-state heat generation example, one can then solve for the thermal contact resistance:

$$q''_x = \frac{T_{w,s} - T_{m,s}}{\frac{L_m}{k_m} + R''_{t,c}} = \frac{122\,^\circ C - 75\,^\circ C}{0{,}029\frac{m^2K}{W} + R''_{t,c}} = 500\frac{W}{m^2}$$

$$R''_{t,c} = 0.065\frac{m^2K}{W} \quad (25)$$

This thermal contact resistance is substantial and is the reason that the mug warmer is not able to heat coffee or any liquids to boiling despite its high surface temperature of ≈12 ˚C at steady-state. As demonstrated in Figure 2, the inside surface of the coffee mug remains below 70 ˚C. It can be beneficial to reinforce to the students that reducing thermal contact resistance can be accomplished using contact grease or increasing surface contact between the mug and the warming plate.

Heat Transfer from Extended Surfaces (Fins)

CPU passive heat sinks are excellent small examples of fins. Smaller ones fit nicely onto the coffee mug warmer and have copper bases for increased conduction away from the processor. The text by Incropera and DeWitt has a number of example problems using passive heat sinks that help reinforce what the students observe.[1]

<u>Experimental Procedure:</u>

1. *Allow the plate warmer to heat up and reach steady-state (about 15 minutes to reach T_{ss} ≈120 ˚C).*
2. *Measure initial temperature reading of fin tip and record this as time 0.*
3. *Place the CPU passive heat sink on the mug warmer and start the stopwatch.*
4. *At 15-second intervals, record the temperatures of the same fin tip or, alternatively, allow the system to reach equilibrium while class lecture / discussions continue.*
5. *Continue to take readings until the mug warmer temperature is constant for 45 seconds and reaches steady-state.*

<u>Analysis:</u>

Time-dependent fin-temperature expressions are not typically a part of undergraduate Heat Transfer courses. Therefore a rigorous analysis of the data in Figure 3 is not included here. It would be ideal to be able to determine temperature as a func-

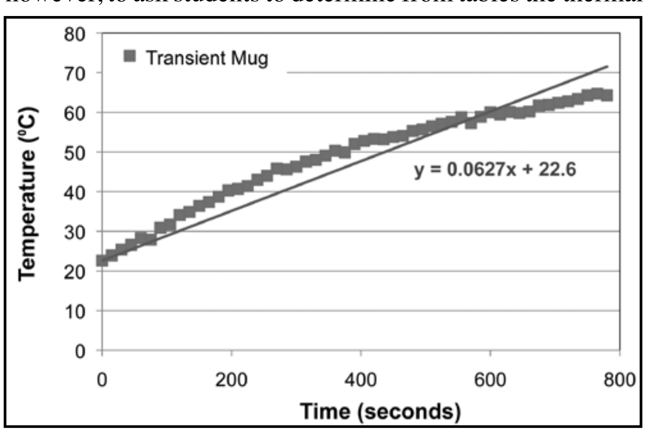


Figure 2. *Transient heating of a standard coffee mug on a preheated mug warmer.*

tion of position, but this is not possible with the IR thermometers used in this experiment. This system can, however, still be used as an illustrative visual aid when discussing heat transfer from fins. Most CPU heat sink fins are of uniform cross-sectional area and the following equations are valid for this geometry. The tip is assumed to experience convective heat transfer and so the steady-state, position-dependent temperature distribution with this boundary condition is:

$$T(x) = T_{\infty,\text{ambient}} + \left(T_{w,s} - T_{\infty,\text{ambient}}\right)\frac{\cosh m(L-x) + \frac{h}{mk}\sinh m(L-x)}{\cosh mL + \frac{h}{mk}\sinh mL} \quad (26)$$

and the steady-state fin heat transfer rate is:

$$q_{\text{fin}} = M\frac{\sinh mL + \frac{h}{mk}\cosh mL}{\cosh mL + \frac{h}{mk}\sinh mL} \quad (27)$$

where $m = \sqrt{\frac{hp}{kA_c}}$ and $M = \left(T_{w,s} - T_{\infty,\text{ambient}}\right)\sqrt{hpkA_c}$ and p = fin perimeter while A_c = fin cross sectional area.

Convection

Convection can be included by using a CPU fan on top of a passive CPU heat sink. Most fans are 3 Pin, 9V, or 12V, which can be connected directly to a 9V battery adapter (can be purchased from RadioShack) by splicing together the red wires and the black wires and ignoring the yellow (control) wire. A 12V fan will simply run at a lower speed on a 9V battery. Videos from YouTube are particularly good at demonstrating external flow past rods or fins.[8]

This section covered demonstrations and student experiments for steady-state, 1-D conduction in both a composite system and considering contact resistance, heat generation from both a transient and steady-state perspective, and heat transfer from fins with and without forced convection. Some demonstrations are relatively quick (5 to 8 minutes) while others involving transient temperature changes can take 15 to 20 minutes to complete. Since the same basic materials are used throughout the course to illustrate the different concepts, student familiarity with the tools increases and thus the students' efficiency at conducting experiments increases through the semester. The advantage of repeatedly using the same system to illustrate different aspects of thermal energy flow is apparent when the students begin integrating concepts into a coherent framework.[9]

CONCLUSIONS

A versatile hotplate conduction and convection system is outlined as a Desktop Experiment Module. These DEMos can be useful tools to introduce students to heat transfer concepts in a complementary fashion to the traditional Heat Transfer lecture course. This article briefly discussed the course structure and content as well as the straightforward desktop experiments, which utilized inexpensive supplies to demonstrate thermal energy motion in solid materials, fins, convective heat transfer from solid surfaces, and radiation. Advantages of this hands-on experience include that it is not dependent on the availability of lab space and students have a unique experience to link into their evolving understanding of chemical engineering concepts. A supply list, instructional procedure, and lab mats were briefly discussed; full versions are available for instructor use upon request.

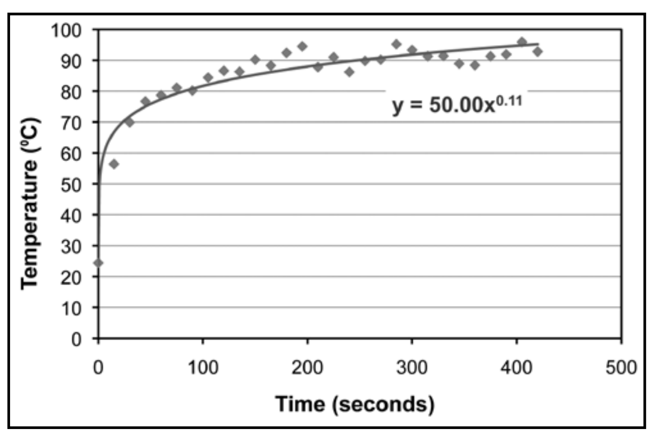


Figure 3. *Transient heating of a heat sink fin with time. The variability in temperature at steady-state is likely due to the difficulty reading temperatures at the same fin location.*

REFERENCES

1. Incropera, F.P., D.P. DeWitt, T.L. Bergman, and A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, 6th Ed. (2007)
2. Minerick, A.R., "Desktop Experiment Module: Heat Transfer," Chemical Engineering Division - American Society of Engineering Education *Proceedings*, Austin, TX, June 2009
3. Minerick, A.R., and K.H. Schulz, "Freshman Chemical Engineering Experiments: Charged up on Electrophoresis & Brewing with Bioreactors," Chemical Engineering Division - American Society of Engineering Education *Proceedings*, June 2005
4. Minerick, A.R., and K.H. Schulz, "Freshman Chemical Engineering Experiment: Charged up on Electrophoresis," American Society of Engineering Education Southeast Regional Conference *Proceedings*, April 2005
5. Desktop Experiment Modules (DEMos), M.D.-ERL, <http://www.che.msstate.edu/research/MDERL/demos.php>, accessed Feb. 6, 2009
6. Hestekin, C., and J. Hestekin, Dept. of Chemical Engineering, University of Arkansas, Spring 2008-present
7. Polycarbonate, Wikipedia, <http://en.wikipedia.org/wiki/Polycarbonate>, accessed March 18, 2009
8. YouTube (online video sharing site) <http://www.youtube.com/>, accessed Feb. 5, 2009
9. Toghiani, R.K., A.R. Minerick, and K.B. Walters, "Making the Connections: Facilitating Student Integration of Chemical Engineering Concepts into a Coherent Framework," 2008 ASEE Conference *Proceedings* ❒

ENGAGING K–12 STUDENTS IN THE ENGINEERING CLASSROOM:
A Creative Use of Undergraduate Self-Directed Projects

Omolola Eniola-Adefeso
University of Michigan • Ann Arbor, MI 48109

Engineering, along with science, has been the engine that drives innovation and will continue to be important in tackling the new and unique transportation, environmental, and health problems that we face as a global society. For the United States to stay relevant in the new "global economy" we must position ourselves to take a lead in tackling these problems and the key is to maintain strength in our "human capital."[1] Yet, the United States continues to lag behind other developed nations in the quality of its workforce. For one, only 5% of undergraduate (UG) students in the United States currently receive their degrees in engineering compared to ~50% in some other countries.[1] Furthermore, nearly 62% of all Ph.D. degrees in engineering granted in the United States in 2007 were to foreign students but visa regulations make it difficult for them to stay in the United States.[2] Continuing on this course will lead to fewer engineers with high-quality skills available to lead innovation in the United States.[1]

One major contributing factor to the low number of students receiving degrees in engineering is the two decades of decline in student enrollment in engineering. While there has been some recent improvement in enrollment due to the current global recession highlighting the apparent stability of engineering jobs,[3] the United States is still projected to face a shortage of up to 70,000 engineers in this decade.[1, 4] Recent surveys by the American Society for Quality (ASQ) and the National Academy of Engineering (NAE) suggest that this shortage and decline in engineering enrollment is linked to K–12 students having little knowledge of engineering careers in addition to perceiving engineering as "boring."[5] The NAE study further concluded that the money and effort put forth by engineering organizations to combat this problem have had little impact. Overall, what is clear from the literature is that boosting undergraduate enrollment and increasing the number of graduates in engineering are two key parameters in keeping the United States competitive in the global economy of the 21st century and beyond. Thus, additional effort needs to be placed on making the new generation of K–12 students aware of the engineering profession and its versatile contributions to solving many critical global issues.

__Omolola Eniola-Adefeso__ is an assistant professor of chemical engineering at the University of Michigan. She received a B.S.E. from University of Maryland Baltimore County (UMBC) and a Ph.D. in chemical engineering from the University of Pennsylvania with graduate research support from NASA GRSP. Her research interests include shear-dependent adhesion and migration of leukocytes and design of cell mimetics for vascular-targeted drug delivery.

The two most common outreach tools used in presenting engineering to the public are 1) professional engineers or engineering faculty spending time in the K–12 classroom to talk about their profession and 2) informal educational programs (*e.g.*, tutoring) focused on improving students' understanding of math and science.[5] Visits from engineering professionals, however, often leave students unable to see a path for themselves to achieve the level of success perceived in their corporate/university visitors. Likewise, tutoring/mentoring outreach efforts often fail to connect K–12 students back to the engineering—*i.e.*, heavy focus on math and science. Presented herein is a different approach to introducing K–12 students to and exciting them about chemical engineering, where a required undergraduate chemical engineering (ChE) course project is coupled with a science fair style presentation to local high school students. Specifically, students enrolled in the Mass and Heat Transfer (M&HT – ChE 230) course at the University of Michigan (U of M) in groups of four were asked to design and present one original experiment suitable for a high school teacher to use in introducing a basic heat or mass transfer concept to his/her high school science class. Each student group was provided a $25 budget to build their experiment, and local high school students from the Ypsilanti school district were invited into the classroom to experience and judge ChE students' design outcome on its ability to engage their interest in engineering as a career choice. This paper discusses the success, benefit, and practical suggestions for replication of this unique approach to K–12 outreach.

A

ChE 342 Fall 2008
Group Project Evaluation Sheet
(High School Participant)

Group No. ________________**Project Title** ______________________________

On the scale of 1 - 10 (10 = highest score);

How original was the experiment? (Q1)

How relevant is this experiment for introducing heat and mass transfer principle to you? (Q2)

How excited were you by the experiment? (Q3)

How engaged were you with the experiment? (Q4)

Did you learn something new? (Q5)

How successful was the experiment is getting you interested in Engineering? (Q6)

How likely are you to be able to repeat this experiment in your classroom if provided the materials? (Q7)

B

ChE 342 Fall 2008
Group Project Evaluation Sheet
(Graduate and Faculty Participant)

Group No. ________________**Project Title** ______________________________

4 = Excellent; 3 = Good; 2 = Partial; 1 = Attempt made; 0 = Absent

Creativity (Q1)					
Does the group project or display demonstrate ingenuity in the design and development?	4	3	2	1	0
Has the students shown creativity in the design	4	3	2	1	0
Scientific Thought (Q2)					
Is the experiment appropriate for the study of heat and mass transfer principles?	4	3	2	1	0
Is the experimental goal clearly stated?	4	3	2	1	0
Has appropriate controls been made?	4	3	2	1	0
Were the observations and information gained clearly summarized?	4	3	2	1	0
Does the data collected justify the conclusion made?	4	3	2	1	0
Thoroughness (Q3)					
Is the project the result of careful planning?	4	3	2	1	0
Does the project indicate a thorough understanding of the chosen topic?	4	3	2	1	0
Does the experimental design/setup reflect students' originality?	4	3	2	1	0

On the scale of 1 - 10 (10 = highest score);
How relevant is this experiment for introducing heat and mass transfer principle to high school student? (Q4)
Can the proposed experiment be easily reproduced in a high school classroom/laboratory setting? (Q5)
How safe is the proposed experiment for a high school classroom/laboratory setting? (Q6)
How economical is the experimental setup? (Q7)

Figure 1. *(A) High school student survey and (B) faculty, teacher, and graduate student survey.*

METHODS

Project Description. For their course project, students enrolled in the M&HT course at U of M, in groups of four, were asked to design an original experiment that would be suitable for a high school teacher to use in introducing a mass or heat transfer principle/concept to students in her/his class. Students were assigned to groups semi-randomly where self-selected pairs were randomly matched to form groups of four. Groups were asked to design their experiment such that it can serve to attract high school students to ChE. Experimental design was subject to the following constraints: i) experiment must be feasible; ii) materials/setup cost for the experiment must not exceed $25; and iii) designed experiment must be easily set up in a high school classroom. Each group was required to present an in-class demonstration (demo) of their experiment at the end of the semester to a diverse audience composed of local high school students and teachers and chemical engineering graduate students and faculty. Groups were also required to submit a five-page comprehensive written description of their design.

Project report. For the written project description, groups were required to include a rationale for the design, a detailed list of required materials, and a description of the experimental setup. In addition, groups were asked to include any experimental measurements taken during the design process, describe all relevant mass/heat transfer equations, and include their expected experimental outcome(s) and conclusions.

Project presentation. The in-class demo format was less stringent; groups could have one demo that is reused for multiple sets of judges or multiple disposable (inexpensive) setups. Furthermore, in-class demos could not include the use of any hazardous materials (*e.g.*, organic solvents) or high temperature/pressure experiments. Groups were provided a budget of $25 (see project description) to obtain materials for their in-class demos and given access to a senior engineer within the department to provide guidance on setups and choice of materials.

Grading. Projects were graded on originality, feasibility for reproduction in a high school classroom, and the quality of the in-class demo. The written report counted for 75% of the total project grade and the in-class demo for 25%. Total project grade was given on a 100-point scale and represented 10% of the final course grade. The project presentation grades were derived from surveys (Figure 1) administered to guest participants that included high school students (HSS), their teachers, and ChE graduate students and faculty. The survey to HSS focused on evaluating the ability of ChE student-designed experiments/demos to excite and engage HSS about chemical engineering, and the survey to the faculty team (including HS teachers and ChE graduate students) focused on evaluating the creativity, scientific thought, thoroughness, and the fitness of the demos for a high school audience. To ensure that each student group gets an adequate number of HSS viewing their demo during the presentation window (2 hours), HSS were given survey sheets prefilled with ChE group numbers, and each HSS was required to visit at least five teams.

Recruitment of High School and ChE participants. High school participants were recruited from the Ypsilanti local school district via the University's Office of Engineering Outreach and Engagement – (OE).[2] The group consisted of 15 10th–11th graders enrolled in the general chemistry class and their teachers (2). Participating HSS were only required to have a B average in the chemistry course. Graduate students (4) and faculty judges (5) were recruited within the Department of Chemical Engineering via e-mail solicitation.

Data Analysis. The University of Michigan Internal Review Board approved all surveys used in assessing the outcome of the course project. Numerical values from surveys were converted to a 100-point scale and averaged over all surveys submitted for individual groups. Significance of data was assessed via a student's t-test with p value < 0.05 considered significant.

RESULTS

ChE student project outcome. There were 115 students enrolled in the Fall 2008 M&HT course; thus, a total of 29 teams participated in the class project. Group assignments and the project description were available to students by the third week of classes. Groups had the freedom to select any mass or heat transfer principle as a basis for their design and were encouraged to consult with the course instructor on the scope, scale, and feasibility of their projects. About a third of the groups based their experiments on mass transfer principles, and two teams attempted experiments involving both mass and heat transfer. Ten teams consulted with the instructor on various aspects of their designs prior to the in-class presentation. The average written report score for teams that sought instructor input was not significantly different from the average for teams that did not—92.9% vs. 94.2% ($p = 0.46$). Similarly, the average presentation score for groups that consulted with the course instructor (78.6%) was not significantly different from the average for groups that did not (80.9%). There was also no significant difference in the presentation scores (average of all surveys) between mass or heat transfer based experiments.

Overall, many student groups offered a unique and fun take on several mass and heat transfer principles. For example, the team with the highest project score designed a simple, yet effective, experiment to illustrate the basic principles of conductive heat transfer. Specifically, this group set up a station for HSS to cut through ice using body heat that was delivered to the ice via a heat-conducting material. By varying the type of material used (graphite, aluminum, and plastic) and contact area between the body and the material (one vs. two fingers), the group was able to explain Fourier's law for heat conduction to 10th-11th graders. For instance, a deeper cut into the ice by a particular material would suggest to the HSS that the material has a higher heat conductivity compared to other materials. The fact that many of the HSS (and at least one ChE faculty) expressed their surprise that graphite conducted heat much faster than aluminum highlighted the success of this particular demo in achieving the project goal. Table 1 lists titles and topics of other noteworthy student-designed experiments. Details of these and other successful projects with instructions for replication in the high school classroom can be found at <http://che.engin.umich.edu/people/eniola/projects.html>.

There were two major drawbacks to the science fair style project presentation: 1) the large class size made it difficult to set up demo stations in a way that allowed easy access for judging and 2) the large number of demos requiring access to electricity. These two issues led to brief periods of chaos during project presentation.

ASSESSMENT

High school student (HSS) survey outcome. Fifteen HSS from the YPSD school district participated in the project presentation. Of these, 10 were female and eight were African-American. The average overall GPA of the group was 3.0 with seven of the students having their GPAs below 2.0.

The judging process required that each HSS fill out a survey immediately after each demo viewed to ensure an accurate representation of their opinions. Four key questions were used on the HSS survey (Q3 - Q6 in Figure 1A) to gauge how successful a group's demo was at introducing and engaging

TABLE 1
Sample Project Designs by ChE Student Teams

Group Project Title	Heat/Mass Transfer Concept Presented
The Reindeer Effect	The experiment demonstrates the ability of a microwave to provide heat to a system through electromagnetic radiation
Molecular Diffusion Through a Porous Medium	Dependence of mass diffusivity on temperature
"Once You POP, You Can't STOP"	Dependence of mass transfer flux on temperature and convection via carbon dioxide in liquid soda pop (visual demonstration of transfer using balloons)

HSS interest in chemical engineering. Figure 2 summarizes the level of excitement and engagement reported by the HSS. About two-thirds of the HSS' encounters with demos resulted in the HSS feeling fairly to highly excited about or engaged with the viewed presentation. More importantly, 83% of encounters resulted in the HSS feeling they learned something new. Overall, nearly 70% of encounters left HSS feeling fairly to highly interested in engineering.

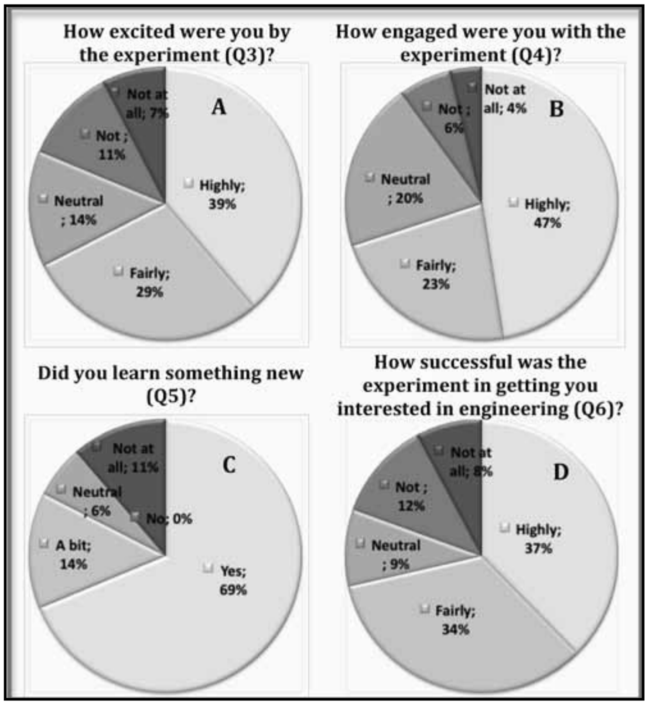


Figure 2. Summary of high school student survey on excitement and engagement rated on a scale of 1 –10. Highly (Yes) = 9 – 10; Fairly (A bit) = 7 – 8; Neutral = 5 – 6; Not (No) = 3 – 4; Not at all = 1 – 2.

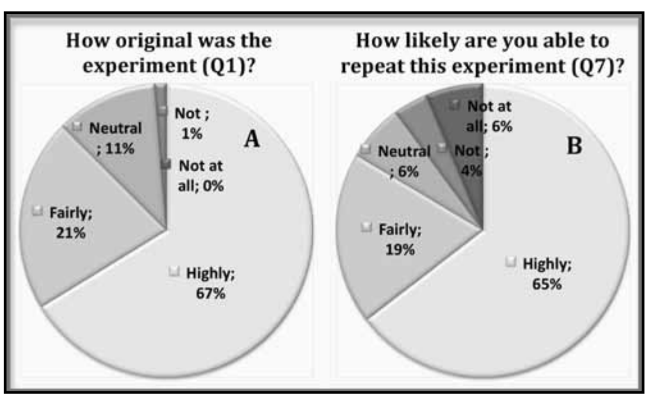


Figure 3. Summary of HSS survey gauging how well ChE designs adhered to the project statement. Highly = 9 – 10; Fairly = 7 – 8; Neutral = 5 – 6; Not = 3 – 4; Not at all = 1 – 2.

Questions 1 and 7 on the HSS survey were used to gauge how well ChE student designs adhered to the project problem statement and imposed constraints (see the section on "Methods"). Figure 3 shows that 88% of HSS encounters resulted in a "fairly to highly original" rating of the viewed demo, and 84% of encounters resulted in a "fairly to highly likely" rating on HSS perceived ability to repeat the viewed demonstration in their high school classroom.

Faculty team survey outcome. Graduate students, high school teachers, and ChE faculty members were invited to evaluate the technical aspect of designed experiments and their fitness for the high school classroom via the survey shown in Figure 1B. Only two HS teachers participated in the project presentation survey. The responses to Q1-3—focused on evaluating ChE student designs for creativity, scientific

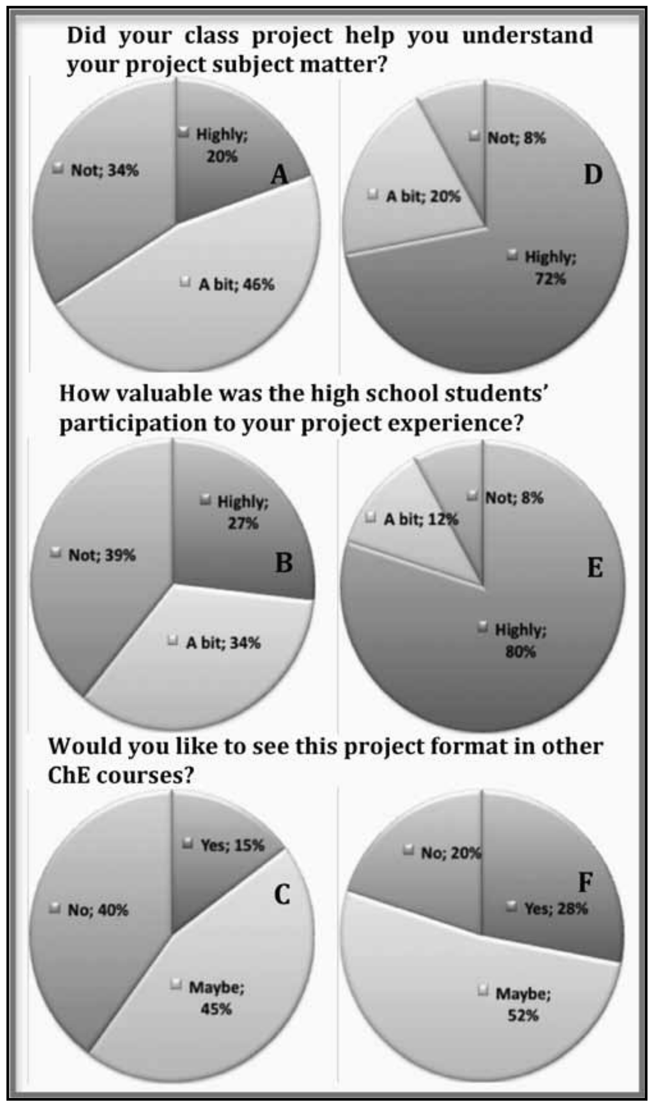


Figure 4. Summary of ChE student end-of-course (A-C) and post-semester (D-F) surveys scale.

TABLE 2
Faculty Team Survey Result for Q1 – Q3

		Excellent	Good	Partial	Attempt made	Absent
Creativity	Does the group project or display demonstrate ingenuity in the design and development?	41.9%	41.9%	16.3%	0.0%	0.0%
	Have the students shown creativity in the design?	41.9%	37.2%	18.6%	2.3%	0.0%
Scientific Thought	Is the experiment appropriate for the study of heat and mass transfer principles?	62.8%	32.6%	4.7%	0.0%	0.0%
	Is the experimental goal clear?	65.1%	27.9%	7.0%	0.0%	0.0%
	Has appropriate control been made?	46.5%	34.9%	18.6%	0.0%	0.0%
	Were the observations and information gained clearly summarized?	48.8%	32.6%	18.6%	0.0%	0.0%
	Does the data collected justify the conclusion made?	46.5%	30.2%	20.9%	2.3%	0.0%
Thoroughness	Is the project the result of careful planning?	37.2%	46.5%	11.6%	4.7%	0.0%
	Does the project indicate a thorough understanding of the chosen topic?	53.5%	25.6%	20.9%	0.0%	0.0%
	Does the experimental design/setup reflect students' originality?	44.2%	34.9%	20.9%	0.0%	0.0%

thought, and thoroughness—are summarized in Table 2. Overall, faculty responses to Q1 – 3 were mostly "good" to "excellent" (79 – 95% of the time). About 82% of the faculty team's encounters with demos resulted in a "fairly to highly relevant" rating in response to Q4 of the survey. Furthermore, over 90% of the time, the faculty team responded to Q5 through Q7 with a "fairly to highly likely" rating, suggesting a general feeling that most student teams were successful in designing an economical experiment that is safe and can be easily reproduced in a high school classroom (not shown). The two HS teachers that participated in the project presentation were also asked to respond to Q7 on the HSS survey. Of the six demos they viewed, the two teachers felt that they could "fairly to highly likely" repeat three in their classroom, they were neutral on two, and felt they were not likely to be able to repeat one in their classroom. Interestingly, the experiment rated low on adaptability to their high school classroom was also rated "neutral" on originality and "not at all" on whether they learned something new or its ability to engage their interest in engineering. Thus, it is possible that their perceived inability to repeat this particular experiment in the classroom is linked to their lack of excitement for the demo.

ChE student survey outcome. Since the class project/outreach event described herein is new to students enrolled in the M&HT course, it was important that their view of the project format be collected. To this end, the ChE students were surveyed twice—first on the last day of classes prior to the final exam and a second time at end of the Winter 2009 semester (~ 4 months after in-class presentation). Both surveys were voluntary with responses collected anonymously. A total of 100 students participated in the end-of-term survey and 50 in the post-fall semester survey (post survey). Three key questions were repeated in both surveys to evaluate potential change in student opinion over time. Figure 4 (previous page) shows pie charts comparing the outcome of questions between the two surveys. When asked if their project experience helped their understanding of their project subject matter, 72% of the post survey respondents were highly positive compared to 20% of the end-of-term survey respondents. Similarly, respondents on the post survey showed a greater enthusiasm for HSS participation in their project presentation (80% post-semester vs. 27% at the end of term). Students' feeling about having this type of project format in other ChE courses at Michigan likewise shifted in the positive direction with only 20% of respondent saying "no" on the post survey compared to 40% on the end-of-term survey. The overwhelming improvement in ChE students' attitude towards the class project in the post survey may not be representative of the entire class, however, since only 44% of the class participated in this survey compared to the 87% participation for the end-of-term survey. Thus, it is plausible that students who previously had a positive view of the class project were disproportionately represented on the post survey. Even if this were the case, however, the views of these students appear to be more positive on the post survey as compared to the end-of-term survey, *e.g.*, only 20 students on the end-of-term survey thought the project helped their understanding of their course material vs. 36 students that felt the same way on the post survey.

A set of questions was asked only on the post survey to gauge students' feeling on the impact of the M&HT project on the outcome of their winter semester courses. Of the 50 students taking the post-semester survey, 38 indicated they were currently enrolled in the junior ChE lab course, and 32% of these students indicated that their M&HT project experience was "highly" valuable to their winter lab course (Figure 5). Only 24% of all post-survey respondents, however, indicated that their ChE project experience was "highly" valuable to other courses in which they were currently enrolled. When asked how likely they were to consider participating in other K–12 outreach programs if their class project presentation were categorized as outreach, 60% of post-survey respondents indicated they were highly likely to do so compared to only 8% indicating they were not likely to participate. Overall, students who had a positive feeling about the course project on the post survey did so regardless of their course grade outcome, *e.g.*, 40% of post-survey respondents felt their H&MT grade was worse than expected compared to 20% saying they do not want to see this sort of project in other engineering courses. Finally, some ChE students offered positive opinions about the class project outside of the survey questions. For example, one student wrote "the class project showed us how diverse the things are that we chemical engineers can actually do" and another said "I got the opportunity to talk about the class project at an interview so I was glad that we did the project."

Comparison to other science fair style outreach programs. Many universities (and companies) also have on-site outreach programs that allow K–12 interaction with college

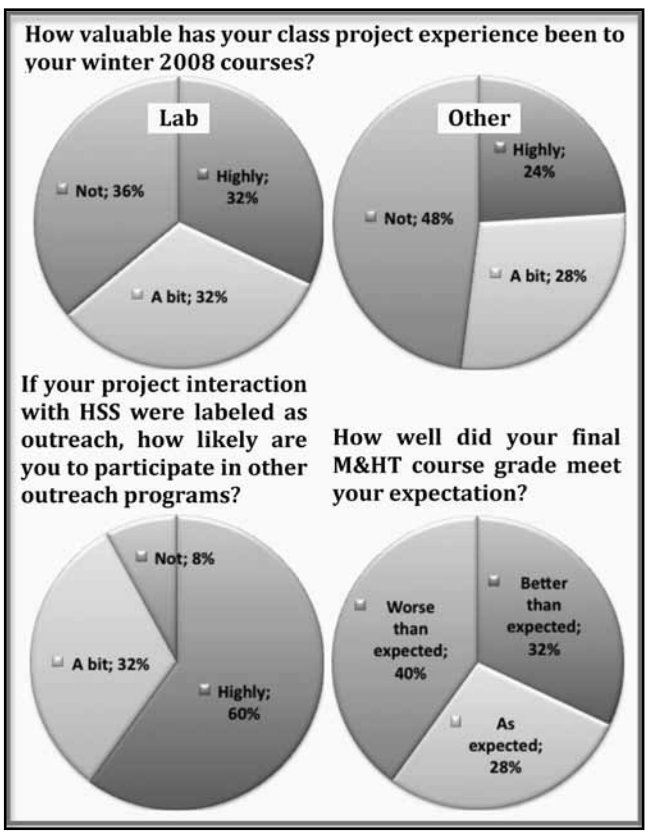


Figure 5. *Summary of ChE student's response to questions unique to the post-semester survey.*

students and professionals. Two prominent examples of this are: 1) the University of Illinois at Urbana-Champaign's College of Engineering annual science fair style open house aimed at "showcasing the talent and ingenuity" of their engineering students to the public,[6] and 2) the engineering expo at Kansas University. Students, student groups, and faculty across the engineering college participate in these outreach events by way of presenting demos, hosting engineering-themed competitions, tours of facilities, and informational sessions. Although the in-classroom outreach program presented herein is not meant to replace or compete with such elaborate events, it can offer unique advantages to K–12 outreach. For one, the presented in-classroom event may be a great way for a department to incorporate outreach into their program in the absence of a college-wide event similar to the ones mentioned above. Secondly, while the in-classroom event cannot reach as large an audience as a college-wide (or campus-wide) event, it can offer an opportunity for a more intimate interaction between K–12 and engineering students. Specifically, the large college-wide event can run the risk of being viewed similar to a spectator sport where the visiting K–12 students are exposed to elaborate finished products perceived to be created by incredibly bright engineering students, but are not able to see themselves with the capacity to perform at such level. In a classroom setting, the K–12 visitors are exposed to 1) all types of students and their vulnerabilities, 2) simple projects focused on showcasing engineering aspects of day-to-day life as opposed to the "cool and fancy" things engineering can make, and 3) a better sense of the engineering classroom. Moreover, the design criteria imposed on the presented in-classroom outreach (see "Methods") ensures that K–12 visitors are active participants in the experiments as a way to learn key engineering principles, *i.e.*, a successful ChE design is one that can be carried out by K–12 students in their own classroom. Thirdly, the present in-classroom project-outreach event offers the possibility of tracking impact on participating K–12 students and their eventual college enrollment since recruitment is via an official college-school district relationship. Finally, for engineering colleges that do have an on-campus outreach event, the presented outreach approach may serve as a way for departments to involve more of their undergraduates—not just the high achievers—such that they have more demos to showcase and can foster a more intimate interaction between the K–12 audience and engineering students.

CONCLUSIONS

Visual/hands-on demonstrations have long been an effective way of teaching scientific/engineering principles,[7, 8] and the "each-one-teach-one" approach to knowledge transfer has been proven to enhance students' learning experience. Here, we show that these two approaches can be combined to create a unique course project within the chemical engineering curriculum that allows ChE undergraduate students to enhance their understanding of key course concepts while simultaneously exposing HSS to basic concepts of chemical engineering. Both groups of students (HS and ChE) that participated in this unique project presentation/outreach format indicated a better understanding of the demonstrated engineering principles. More importantly, the HS audience (including teachers) indicated an overwhelming interest in chemical engineering as a result of their participation in the ChE course project. Overall, the incorporation of K–12 activities into the chemical engineering course curriculum overcomes the time commitment barrier that often prevents college students and faculty from participating in outreach to K–12. Furthermore, this project-outreach class presentation format likely presents engineering to high school students in a less intimidating manner where these students themselves can get involved with demonstrations of engineering principles. This conclusion is evident in the highly positive response of HSS to the survey question focused on their perceived ability to repeat ChE demonstrations in their own classroom. Bringing HSS into the engineering classroom can serve to demystify the college experience for these visitors. Lastly, while this type of class project-presentation easily lends itself to mass and heat transfer, it can readily be adapted to other chemical engineering courses, including material balance, fluid dynamics, separation, and product design. For example, the hands-on experiment for freshmen in chemical engineering developed by Prof. Hohn at Kansas State University[8] can easily be modified to include a presentation to K–12. Practical tips for replication are listed in Table 3.

ACKNOWLEDGMENT

This work was supported by an NSF (EEC-0824182) grant to Omolola Eniola-Adefeso. The author thanks Dr. Cynthia Finelli, Dr. Camelia Owens, and Prof. Julia Ross for their insight and useful conversations in the development and assessment of the presented class project.

REFERENCES

1. Committee on Prospering in the Global Economy of the 21st Century, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Academies Press (2007)
2. National Science Board, *Science and Engineering Indicators: 2010*, National Science Foundation, Division of Science Resources Statistics, Arlington, VA (2010)
3. Merterns, R., "Engineering Suddenly Hot At Universities," *The Christian Science Monitor*, April 24, 2009 <http://www.csmonitor.com/2009/0424/p02s01-usgn.html>
4. National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century*, National Academies Press (2004)
5. Committee on Public Understanding of Engineering Messages, and National Academy of Engineering, *Changing the Conversation: Messages for Improving Public Understanding of Engineering*, National Academies Press (2008)
6. "Engineering At Illinois" <http://engineering.illinois.edu/about-us/K–12-outreach>
7. Farrell, S., R.P. Hesketh, and M.J. Savelski, "A Respiration Experiment to Introduce ChE Principles," *Chem. Eng. Ed.*, **38**(3) 182 (2004)
8. Hohn, K.L., "The Chemical Engineering Behind How Pop Goes Flat: A Hands-On Experiment for Freshmen," *Chem. Eng. Ed.*, **41**(1) 14 (2007) ❒

TABLE 3
Practical Tips for Project Replication

1.	Project format works best for small to medium class size (although a positive outcome is achievable with a fairly large class as reported herein).
2.	Student should have access to the project description early in the semester to allow ample time for project development.
3.	Instructor may stimulate idea formulation among students via her/his own sample in-class experimental demonstration of course concepts.
4.	Instructor should take care to invite K–12 students at the appropriate level, *e.g.*, middle to high school students are likely appropriate for participation in mass and heat transfer projects while elementary to middle school age students maybe more suitable for any project/outreach associated with an introductory chemical engineering course. Overall, desired K–12 grades can be targeted via the project description and imposed constraints.

Random Thoughts . . .

MEET YOUR STUDENTS
3. MICHELLE, ROB, AND ART

Richard M. Felder
North Carolina State University

Random Thoughts has been running for so long now that many current CEE readers were in elementary school when some of the early columns appeared (which is a pretty frightening thought). Starting now, I'm going to occasionally reach back in the archives and reprint one I think still has relevance. This column is a slightly updated version of one from the summer of 1990.

The scene is the student lounge at a large university. Three juniors—Michelle, Rob, and Art—are studying for the second quiz in the introductory fluid dynamics course. Art got the high grade in the class on the first quiz, Michelle was close behind him, and Rob got 15 points below class average. They've been at it for over an hour.

Michelle: "What about this stuff on non-Newtonian flow—I don't think I really get it."

Art: "I think we can forget it—I've got copies of Snavely's tests for the last five years and he's never asked about it."

M: "Maybe, but it's the real stuff...you want to analyze blood flow, for instance, Newtonian won't work."

A: "So what...the only blood flow we're going to have to worry about is ours on this test if we don't stick to the stuff Snavely is going to ask."

M: "Yeah, but if we don't..."

Rob: "Hey Art, is there going to be any of that Navier-Stokes trash on the quiz?"

A: "Yeah, there usually is, but no derivations—you just have to know how to simplify the equation."

R: "Rats—I hate that garbage."

M: "I've been looking through the text...there are all sorts of Navier-Stokes problems in there—we could try to set some of them up."

R: "Nah, too much grind—I just need to do enough to get my C, my degree, and my MG...Art my man, why don't you haul out those old tests and let's just memorize the solutions."

A: "Okay, but that may not...hey, look at this question—he's used it for three years in a row...Parts (a) and (b) are just plug-and-chug, but he throws a real curve ball here in Part (c)—I don't know how to do it."

R: "How much is Part (c) worth?"

M: "Never mind that—let me see it...okay, he's asking about velocity profile development—you just need to use the correlation for entrance length."

A: "What are you talking about—I never heard of that stuff."

M: "He never talked about it in class but it's in the reading—you need to calculate the Reynolds number and then substitute it in this dimensionless correlation, and that gives you..."

R: "I'm gonna grab a Coke from the machine, guys—when you get it all straight just tell me what formula I plug into, okay?"

A: "Yeah, sure. So it's just this correlation, huh Michelle—do I need to dig into where it comes from?"

***Richard M. Felder** is Hoechst Celanese Professor Emeritus of Chemical Engineering at North Carolina State University. He is co-author of* Elementary Principles of Chemical Processes *(Wiley, 2005) and numerous articles on chemical process engineering and engineering and science education, and regularly presents workshops on effective college teaching at campuses and conferences around the world. Many of his publications can be seen at* <www.ncsu.edu/effective_teaching>.

M: "Probably not for the test, but I was trying to think why you would want to know the entrance length, and it seems to me that if you're designing a piping system that has a lot of short pipe segments it would be important to know how well your pressure drop formulas will work...blood flow again, in capillaries, or maybe lubricating oil in a car engine, or..."

A: "Forget it—that stuff's not going to be on this test...even Snavely wouldn't be that tricky...now look at this problem here..."

* * *

These three students illustrate three different *approaches to learning*.[1]

- Michelle tends to take a *deep approach*, meaning that she tries not just to learn facts but to understand what they mean, how they are related, and what they have to do with her experience.
- Rob almost always takes a *surface approach*, following routine solution procedures but not trying to understand where they come from, memorizing facts but not trying to fit them into a coherent body of knowledge.
- Art's primary goal is to get the highest grade in the class, whatever it takes. He takes a *strategic approach*, which involves finding out what the instructor wants and delivering it—digging deep when he has to, staying superficial when he can get away with it.

Engineering faculty members often complain that most of their students are Robs and pitifully few are Michelles. Unfortunately, few of us do anything in class to stimulate our students to take a deep approach: we just give them tricky tests to see if they can "do more than plug in," and then gripe that they're apathetic and incompetent when they can't. Fortunately, there's something more productive we can do. The following conditions increase the likelihood that students will adopt a deep approach to learning.[1]

- *Student-perceived relevance of the subject matter.* Students will not struggle to achieve a deep understanding of material that seems pointless to them, any more than we would. To motivate them to do it, let them know up front what the material has to do with their everyday lives (*e.g.*, fluid flow in their cars and circulatory systems, heat and mass transfer and reaction in the atmosphere and their homes and respiratory and digestive systems) and with significant problems they may eventually be called on to solve (*e.g.*, fabricating improved semiconductors, developing alternative energy sources, avoiding future environmental catastrophes).
- *Clearly stated instructional objectives, practice, and feedback*. Students are not born knowing how to analyze deeply, and little in their precollege experience is likely to have fostered that ability. To get them to pull meaning out of lecture material and solve problems that go beyond those in the text, spell these objectives out and give concrete examples of the kind of reasoning desired. Then explicitly ask the students to carry out deep analysis in class activities and on homework and give them constructive feedback on their attempts.
- *Appropriate tests*. Provided the preceding conditions have been met, include questions that call for deep analysis on all tests. If the students know they will only get surface questions (closed-ended exercises that require only standard solution procedures), most will likely take a surface approach to learning the material. If they expect some deep questions (more open-ended questions that require greater understanding), most Michelles and Arts and perhaps even some Robs will be motivated to take a deep approach.
- *Choice over learning tasks*. Provide bonus problems and/or optional projects and/or alternatives to quizzes and/or optional self-paced study and/or choices between group and individual efforts.
- *Reasonable workload*. If students have to spend all their time and energy just keeping up, they'll fall back on a surface approach.

The research indicates that by establishing these conditions we may substantially increase the number of our students who think critically about the material we are presenting, try to discover its meaning and its relationship with other material they have previously learned, and routinely question the inferences and conclusions that we present in class. Whether or not we'll know what to do with these people once we have them is a question for another occasion. ❒

---

1 *R.M. Felder & R. Brent. (2005). Understanding student differences. J. Engr. Education, 94(1), 57–72. <www.ncsu.edu/felder-public/Papers/Understanding_Differences.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/

Design Project on CONTROLLED-RELEASE DRUG DELIVERY DEVICES: *Implementation, Management, and Learning Experiences*

Qingxing Xu, Youyun Liang, Yen Wah Tong, and Chi-Hwa Wang
National University of Singapore • Singapore 117576

Over the years, the engineering application of transport phenomena has contributed to research advances in various biomedical and pharmaceutical technologies. Transport processes are important factors in the design and operation of biomedical devices used for sensing, diagnosing, or imaging purposes, as well as applications including drug and gene delivery, biological signal transduction, and tissue engineering. Drug delivery is an emerging field in which chemical engineers have had a major impact, particularly for controlled delivery of pharmaceutical drugs to specific target sites. It has been projected that the demand for drug delivery systems in the United States will expand more than 10% annually to $132 billion in 2012.[1] Growth opportunities for drug delivery systems extend into all therapeutic classes of pharmaceuticals and encompass a wide range of compounds and formulations.

Considerable attention has been devoted to the design and development of drug delivery systems as evidenced by the exponential increase in the number of books, review articles, and research papers published. These drug delivery devices offer definite advantages over conventional modes of delivery, which include: i) reduce systematic toxicity by providing localized delivery; ii) provide precise timing in delivery; iii) protect drugs from *in vivo* metabolism, thus achieving higher drug stability, longer therapeutic effect, and lower dosing frequency; iv) enhance delivery of poorly soluble drugs; and v) increase in cost-effectiveness. In the development of these drug delivery devices, mathematical modeling of the release process is important since it establishes the mechanism(s) of drug release and provides more general guidelines for the development of other systems.[2] Undeniably, many successful controlled-release drug delivery devices have been developed as a result of an almost arbitrary selection of components, configurations, and geometries.[2]

Qingxing Xu *is a Ph.D. student in a joint degree program between the National University of Singapore and the University of Illinois at Urbana-Champaign. He received his B.Eng. (2008) in chemical engineering from the National University of Singapore. His research interests include electrohydrodynamic flow systems, polymeric particles for drug delivery, and mathematical modeling of drug delivery systems.*

Youyun Liang *is a Ph.D. student in a joint degree program between the National University of Singapore and the University of Illinois at Urbana-Champaign. She received her B.Eng. (2008) in chemical engineering from the National University of Singapore. Her research interests include liver tissue engineering with microspheres and hydrogels.*

Yen Wah Tong *is an associate professor in the Department of Chemical and Biomolecular Engineering and the Division of Bioengineering at the National University of Singapore. He received his Ph.D. (2000) in chemical engineering from University of Toronto and his B.A.Sc. (1995) in engineering chemistry from Queen's University (Canada). His research interests include polymeric particles for tissue engineering and drug delivery, bioseparation, and membranes.*

Chi-Hwa Wang *is an associate professor in the Department of Chemical and Biomolecular Engineering at the National University of Singapore. He received his Ph.D. (1996) and M.A. (1993) in chemical engineering from Princeton University, his M.Sc. (1991) in biomedical engineering from Johns Hopkins University, and his B.Sc. (1987) in chemical engineering from National Taiwan University. His research interests include solid/liquid separation, drug delivery systems, and flow and dynamics of granular materials.*

This paper describes the introduction of a drug delivery project in a mass transfer course. Farrell and Hesketh[3] have similarly explored the drug delivery field in the freshman curriculum and in a senior-level elective. The authors reported an experiment that involved drug release from a lozenge formulation, and the students were required to determine the drug concentration as a function of time, evaluate the drug dissolution rate, and compare between experimental and model data. Besides drug delivery, there are also other interesting daily-life examples that have been reported by various authors to illustrate the concepts of heat and mass transfer, which include i) processing of ice cream,[4] ii) cooling of a cup of coffee,[5] iii) cooking of potatoes,[6, 7] iv) drying of a bath towel,[8] and v) microwave drying.[9] Mass transfer phenomenon may also be illustrated via simple experiments to determine liquid[10] or vapor[11-13] diffusion coefficients, or via complex equipment to evaluate oxygen transfer in a bioreactor[14] or diffusion across a membrane.[15, 16]

The main objective of this drug delivery project is to show how the principles of mass transfer are employed in pharmaceutical applications. The project first focuses on introducing students to various fabrication techniques of drug delivery devices, before they proceed with vigorous mathematical modeling of these devices of various geometries. Mathematical modeling of drug release provides insights concerning device shape and size on the effect of the release of drug. As a conclusion, the students can deal with a specific area of interest on controlled release in the open-ended component of the project.

PROJECT DESCRIPTION

The aim of the project is to introduce students to the most important, cutting-edge technologies used in the fabrication of drug delivery systems and provide a practical exercise in the design of these delivery devices using MATLAB® software. The project was initiated as a compulsory component of the undergraduate course CN2125 Heat and Mass Transfer in the Spring semester 2009 at the Department of Chemical and Biomolecular Engineering, National University of Singapore. The cohort had a class size of 246 students (divided into 41 teams, six students per team) and the project constituted a weighting factor of 20% in the course grading.

The project consists of three main sections. For the first section, the teams are required to conduct a review of the research literature on the subject of polymeric micro- and nano-particle fabrication and summarize recent developments on a particular chosen technique. Table 1 shows a description of the various particle fabrication techniques.[17-22]

For the second section, the teams are required to perform vigorous mass transfer calculations for the design of controlled-release drug delivery devices using MATLAB®. Each team is assigned with a specific drug and a corresponding diffusion coefficient. Table 2 shows a list of the assigned drugs for the various teams. In this section, the teams will have to model and simulate for an idealized delivery device with the following assumptions:

- *The drug is uniformly distributed within the delivery device with an initial concentration of 30 mg/cm^3.*

TABLE 1
Brief Description of Various Techniques for the Fabrication Of Polymeric Micro- and Nano-Particles

Fabrication Technique	Description	Reference
Emulsion-based methods	• These methods involve solvent extraction or evaporation from the emulsion containing the polymer. • The emulsion consists of the dispersed organic phase (polymer solution) and the continuous phase (usually an aqueous phase).	[17]
Nanoprecipitation	• It is based on the interfacial deposition of the polymer, followed by displacement of a semi-polar solvent miscible with water from a lipophilic solution.	[18]
Spray-freezing into liquid	• It is a novel cryogenic atomization technology for forming drug-encapsulated microparticles. • It involves spraying the liquid formulation directly into the cryogenic liquid, which results in rapid freezing of the atomized droplets and formation of microparticles. • The frozen particles are collected and lyophilized.	[19]
Spray drying	• The drug is dissolved or dispersed in an organic solution of the polymer which is then nebulized in a hot-air flow. • The solvent is evaporated and dried microparticles are recovered.	[20]
Electro-hydrodynamic atomization (EHDA)	• It is suitable for the preparation of nearly monodispersed microparticles from a solution, containing dissolved polymer and drug, by using an applied electric field.	[21]
Supercritical anti-solvent (SAS)	• The drug is dissolved in an organic solvent and the solution is injected into supercritical carbon dioxide. • The supercritical fluid, due to its high diffusivity, rapidly extracts the solvent and results in precipitating the microparticles.	[22]

- *Once the device is injected or implanted within the human body, it begins to release the drug by a diffusion-limited process with a constant diffusion coefficient.*
- *The resistance to film mass transfer of the drug through the liquid boundary layer surrounding the delivery device surface to the bulk fluid is negligible.*
- *The drug is immediately consumed or swept away once it reaches the bulk solution so that in essence the surrounding fluid is an infinite sink.*
- *The shape and size of the delivery device do not change during the drug-release process.*

The project statement requires the delivery device to have at least 20% of the drug being released to the body within one week. Four geometries of the delivery device made of polymer A have been proposed, which include: i) a sphere with a radius of 3 μm, ii) a cylindrical tablet with a radius of 3 μm and a height of 6 μm, iii) a cylindrical fiber with a radius of 3 μm, and iv) a rectangular cuboid with a length, width, and height of 6, 6, and 7 μm, respectively. The following tasks are assigned:

a. *Plot the drug-release profile for a duration of one week for the different geometries.*

b. *Determine the geometries appropriate for this particular application.*

c. *Plot the drug concentration profile for the different geometries at a time of i) one week, ii) two weeks, and iii) four weeks.*

d. *Discuss the differences in the profiles exhibited by the different geometries.*

Next, it is proposed that the drug is to be encapsulated in a cylindrical tablet of radius 1 μm and height 2 μm made of polymer B (composition and physical properties to be determined by the individual project teams). It has the same initial concentration as the previous part, 30 mg/cm^3. From its drug release profile, it is found that 40% of the drug is released to the body within one week. The following questions are asked:

a. *Determine the diffusion coefficient of the drug in polymer B.*

b. *What is the drug concentration at the center of the device?*

The third section forms the open-ended component of the project in which the teams have the flexibility to qualitatively or quantitatively discuss related controlled-release concepts or ideas gained from the first and second sections of the project. In particular, they can deal in-depth with specific areas of interest, which include but are not limited to: i) the discussion of the limitations of the developed model and its practicability under nonidealized conditions or applications, and ii) the model fitting of experimental drug-release data of the assigned drug obtained from the literature using nonlinear regression, followed by the comparison between model and experimental results. These are some of the suggested topics the teams can undertake. The last section is meant to provide a linkage or coupling of the knowledge gained from the earlier two sections of the project.

SOLUTION

The solution presented here is for the second section of the report. Based on the assumptions described earlier, we can write Fick's second law of diffusion with the associated initial and boundary conditions for a symmetrical drug delivery device as follows:

$$\frac{\partial C}{\partial t} = D\nabla^2 C \qquad (1)$$

Initial condition: $C=C_0=30$ mg/cm^3

Boundary conditions: $C=C_s=0$ (at the surface of the device)

$\nabla C = 0$ (at the centerline symmetry of the device)

where C is the drug concentration, t is the time, D is the drug diffusion coefficient, C_0 is the initial drug concentration, and C_s is the surface drug concentration. The analytical solutions for Fick's second law of diffusion with the described boundary conditions for various simple geometries are readily available in the literature and can be expressed in terms of either infinite summation series or error functions.[23, 24] The solutions in the form of infinite summation series needed for the calculation of drug concentration and release profiles for various geometries are summarized in Table 3.

A diffusion coefficient of 2.50×10^{-15} cm^2/s will be used to illustrate the following sample calculation. By using the expressions presented in Table 3, it is possible to obtain the drug concentration and release profiles for the four geometries

TABLE 2
Different Types of Drugs Assigned to the Teams

No.	Drug
1	Mitomycin C
2	5-Fluorouracil
3	5-Fluorouridine
4	Goserelin acetate
5	Leuprolide acetate
6	Adriamycin
7	Dopamine
8	Dexamethasone
9	Nerve growth factor
10	Bovine serum albumin

TABLE 3

Analytical solutions of Fick's second law of diffusion for various geometries under the described initial and boundary conditions. The symbols used include the following: r is the radial position; x, y, and z are the x, y, and z positions, respectively; J_0 and J_1 are the first kind Bessel function of order zero and one, respectively; $\alpha_n R$ is the nth root of the first kind Bessel function of order zero; M_t is the amount of drug released in time t; M_∞ is the amount of drug released after infinite time.

Geometry	Drug Concentration	Drug Release
Sphere (radius = R)	$\frac{C-C_s}{C_0-C_s}=-\frac{2R}{\pi r}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\left(\frac{n\pi r}{R}\right)\exp\left(-\frac{n^2\pi^2 Dt}{R^2}\right)$	$\frac{M_t}{M_\infty}=1-\frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 Dt}{R^2}\right)$
Cylindrical Tablet (radius = R & height = 2Z)	$\frac{C-C_s}{C_0-C_s}=\frac{2}{R}\sum_{n=1}^{\infty}\frac{J_0(\alpha_n r)}{\alpha_n J_1(\alpha_n R)}\exp(-\alpha_n^2 Dt)$ $\times\frac{4}{\pi}\sum_{p=0}^{\infty}\frac{(-1)^p}{2p+1}\cos\left[\frac{(2p+1)\pi z}{2Z}\right]\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4Z^2}\right]$	$\frac{M_t}{M_\infty}=1-\sum_{n=1}^{\infty}\frac{4}{\alpha_n^2 R^2}\exp(-\alpha_n^2 Dt)$ $\times\frac{8}{\pi^2}\sum_{p=0}^{\infty}\frac{1}{(2p+1)^2}\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4Z^2}\right]$
Cylindrical Fiber (radius = R)	$\frac{C-C_s}{C_0-C_s}=\frac{2}{R}\sum_{n=1}^{\infty}\frac{J_0(\alpha_n r)}{\alpha_n J_1(\alpha_n R)}\exp(-\alpha_n^2 Dt)$	$\frac{M_t}{M_\infty}=1-\sum_{n=1}^{\infty}\frac{4}{\alpha_n^2 R^2}\exp(-\alpha_n^2 Dt)$
Cuboid (length = 2a, width = 2b & height = 2c)	$\frac{C-C_s}{C_0-C_s}=\frac{64}{\pi^3}\sum_{m=0}^{\infty}\frac{(-1)^m}{2m+1}\cos\left[\frac{(2m+1)\pi x}{2a}\right]\exp\left[-\frac{(2m+1)^2\pi^2 Dt}{4a^2}\right]$ $\times\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos\left[\frac{(2n+1)\pi y}{2b}\right]\exp\left[-\frac{(2n+1)^2\pi^2 Dt}{4b^2}\right]$ $\times\sum_{p=0}^{\infty}\frac{(-1)^p}{2p+1}\cos\left[\frac{(2p+1)\pi z}{2c}\right]\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4c^2}\right]$	$\frac{M_t}{M_\infty}=1-\frac{512}{\pi^6}\sum_{m=0}^{\infty}\frac{1}{(2m+1)^2}\exp\left[-\frac{(2m+1)^2\pi^2 Dt}{4a^2}\right]$ $\times\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\pi^2 Dt}{4b^2}\right]$ $\times\sum_{p=0}^{\infty}\frac{1}{(2p+1)^2}\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4c^2}\right]$

as shown in Figures 1 and 2, respectively. Here, only the drug concentration profiles for the four geometries after four weeks will be presented. From Figure 2, it becomes clear that to satisfy the therapeutic requirement of at least 20% of the drug being released to the body within one week, all four geometries can be used. The geometry that has the closest percentage release of 20% is the cylindrical fiber. The differences in the drug release profiles may be attributed to their differences in the specific surface areas. Both the sphere and the cylindrical tablet have the highest specific surface area, followed by the cuboid and then the cylindrical fiber. Both the sphere and the cylindrical tablet have the same specific surface area, thus resulting in almost the same percentage of drug being released to the body during the initial release stage.

In the next part of the question, given the information that 40% of the same drug is released to the body within one week, we need to find the diffusion coefficient of the drug in polymer B. Since it was not possible to rewrite the expression for the drug release equation explicitly to solve for the diffusion coefficient, a trial-and-error method will be used to determine the unknown. It is found that the diffusion coefficient is approximately 3.11×10^{-16} cm^2/s. The drug concentration at the center of the device is close to the initial drug concentration of 30 mg/cm^3.

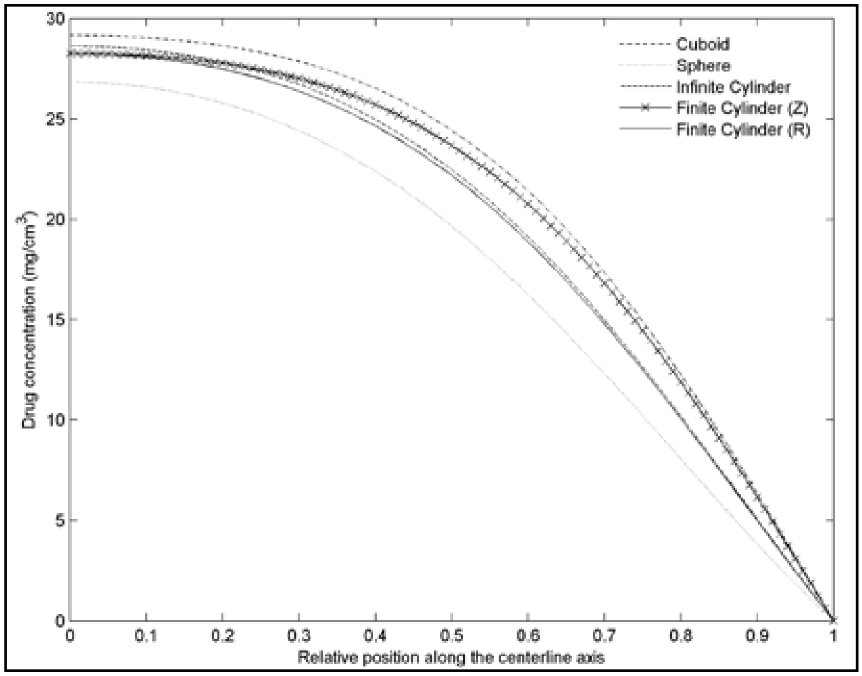


Figure 1. Drug-concentration profiles based on diffusion coefficient of 2.50×10^{-15} cm^2/s for various geometries after 4 weeks. The concentration profile for the cuboid is plotted along the x direction (by setting y = z = 0). The concentration profiles for the sphere and the infinite cylinder are plotted along the radial direction. The concentration profile for the finite cylinder (Z) is plotted along the z direction (by setting r = 0). The concentration profile for the finite cylinder (R) is plotted along the radial direction (by setting z = 0).

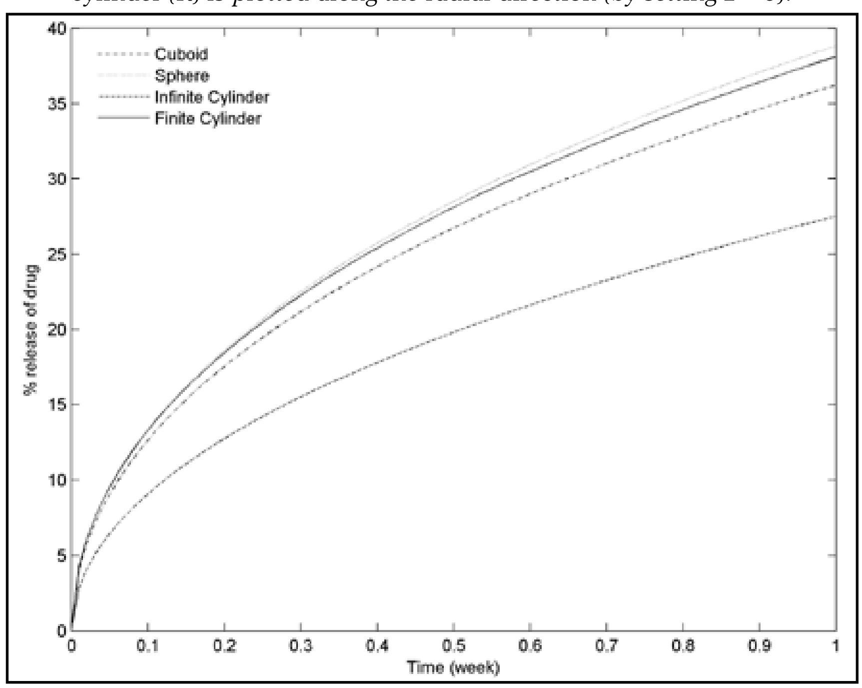


Figure 2. Drug-release profiles based on a diffusion coefficient of 2.50×10^{-15} cm^2/s for various geometries for 1 week. Based on dimensions of the geometries described in problem statement, the specific surface areas for the sphere, cylindrical tablet, cuboid, and cylindrical fiber are 1, 1, 0.952, and 0.667 μm^{-1}, respectively. The corresponding percentages of drug released after 1 week are 38.8, 38.1, 36.2, and 27.5%, respectively.

PROJECT PHASES

For the heat and mass transfer course, a total of three hours of formal lecture and one hour of tutorial class had been allocated per week over 13 teaching weeks (with a recess break during week 7). For the project component, four contact sessions of one hour each were scheduled regularly during the entire phase of the project (12 weeks). The students were organized into teams of six, with two students in each team appointed as the chairperson and vice-chairperson, respectively. The following paragraphs contain more details about the activities planned for the students. The project can be roughly divided into two main phases. It should be noted that some of the tasks had to be carried out simultaneously in order to achieve proper progress.

Phase One (Week 1 Through Week 9)

For the initial phase, attention was focused on the first section of the project. The first contact session scheduled during week 1 was to provide an interesting, enjoyable, and challenging overview of the numerous techniques for the fabrication of micro- and nano-particles to the students. In addition, the students were advised to view a laboratory-made video that was readily available for download from the course website. The video showcased actual experimental setups and explained principles of some of the fabrication techniques available in the current research group. Due to the difficulties in managing first-hand experience on the fabrication techniques for the large body of students, it was hoped that the video would help them understand how the particles were fabricated in the laboratory.

The teams then spent the remaining seven weeks conducting a detailed literature review on a particular fabrication technique before submitting their findings in the form of a five-page mid-term report at the end of week 8. During week 9, sharing sessions were conducted to conclude the first phase of the project. In the sessions, the teams shared their literature findings while the student facilitators provided feedback on the grading of the mid-term reports.

Phase Two (Week 5 Through Week 12)

For the second phase, attention was focused on the second and third sections of the project. Due to the curriculum structure of the course, the topic of mass transfer was covered only during the later part of the semester. Thus, an introduction of the topic to the students was essential for their project work. The second contact session scheduled during week 5 was to introduce the concept of mass transfer and focus on the physics of diffusion.

The students had fundamental backgrounds in MATLAB® programming that was covered during their first-year undergraduate course. The third contact session scheduled during week 9 was to review some of the important MATLAB® commands and syntaxes that would be used frequently in their projects. Much of the time was focused on the introduction of Bessel functions and roots that were needed for the simulation of drug concentration and release profiles for cylindrical geometries.

Office and phone consultations were announced at the start of week 5, mainly to provide technical assistance for the project. Weekly office consultations of one hour each were conducted on week 5 and from week 8 through week 12. Apart from the official consultation hours, the teams could request further meetings or follow-up meetings with the student facilitators whenever necessary.

When the project phase reached week 12, there had been numerous e-mails and office enquiries related to mass transfer concepts and MATLAB® troubleshooting. These questions were clarified and shared during the last contact session scheduled during week 12. This was done so that the rest of the teams would benefit from the answers. The teams submitted their 20-page final reports at the end of week 12.

ROLES OF MANAGERS AND STUDENT FACILITATORS

The project was administered by two managers and two student facilitators. The managers were the course lecturers and their main roles were to oversee the overall project management, supervise the teams, and advise the student facilitators. The managers conducted the first contact session and introduced various techniques for the fabrication of micro- and nano-particles. They were also in charge of maintaining the course website. In particular, the website was updated regularly with important project announcements, essential contact session materials, relevant project references, and most importantly an up-to-date compilation of frequently asked questions based on the e-mail enquiries sent by various teams. The compilation of the frequently asked questions provided several benefits to the overall project management, which include: i) to ensure the information was available and communicated to every team, ii) to allow the teams to learn based on the problems or questions raised by others, and iii) to lighten the e-mail load of the management team by minimizing the need to answer similar questions raised by different teams.

Small sharing sessions were also led by the managers, together with the student facilitators, after the teams had submitted their mid-term reports. Those teams that focused on the same area of fabrication technique were grouped in the same sharing session. In each session, the teams shared their literature findings and any enquiries they had about the fabrication techniques. In addition, the student facilitators provided feedback on the grading of the mid-term reports. In doing so, a two-way exchange of knowledge between the students and the management team was possible.

The main role of the student facilitators was to conduct the remaining three contact sessions with the relevant teaching materials needed for the project. Moreover, they had expertise in MATLAB® programming and were able to provide technical assistance to the teams. The office and e-mail consultations were also handled by the student facilitators. At the end of the project phase when the final reports had been submitted, all of the managers and student facilitators participated in grading the reports and in finalizing the overall marking for the project.

PROJECT ASSESSMENT

The project constituted 20% of the overall assessment of the course, with the rest composed of assignments, quizzes, and final examination. For the first section on the review of research literature, reports were graded based on the comprehensiveness of the review, the ability to integrate information from multiple sources, and the validity of the various points raised.

For the second section, the reports were graded based on the ability to explain the methodology and justify the assumptions and the choice of equations, the accuracy of the solutions, and the discussion of the simulation results. A good discussion should include explanations for the differences in drug concentration and release profiles for the various geometries in terms of their specific surface areas.

The final section was an open-ended component and there was no fixed set of grading criteria. Instead, the reports were graded based on the innovative linkage or coupling of the earlier two sections of the project and the ability to justify those claims. In one particular report, the team recommended a particular fabrication technique for the encapsulation of the assigned drug, with the consideration of factors such as: i) the operating conditions of the fabrication process (*e.g.*, temperature and pH); ii) the properties of the drug (*e.g.*, solubility, hydrophobicity, and stability); and iii) the typical drug-release rates and thus, the therapeutic window of the target drug. The selection of an appropriate fabrication technique was important since some of the conditions would sometimes result in the loss of biological activity of the drug being encapsulated. In another report, the team used the skills gained from the second section of the project to model several experimental results based on the assigned drug and the selected fabrication technique from the literature. Given the published drug release profiles, the team was able to estimate the corresponding diffusion coefficient of the encapsulated drug. The two projects listed here are some of the best reports and serve as outstanding examples.

OUTCOMES/RESULTS

Most of the teams were capable of providing detailed discussions and integrating information from multiple sources for their literature reviews. It was commendable as the students were only in their second undergraduate year and did not have prior experience in the research area. For the design calculations, many teams found them to be particularly challenging and had difficulty developing the necessary MATLAB® codes. Although the students had prior experience in MATLAB® programming, the translation of a descriptive problem statement into a working MATLAB® code was not a skill in which they were proficient. In the design calculations, some of the common errors made included the use of wrong equations, incorrect units, and insufficient terms in the summation series to reach convergence. In addition, a few teams could not determine the correct Bessel roots. Some of them had MATLAB® codes that produced repeated Bessel roots, thus resulting in incorrect drug concentration and release profiles for the cylindrical geometries.

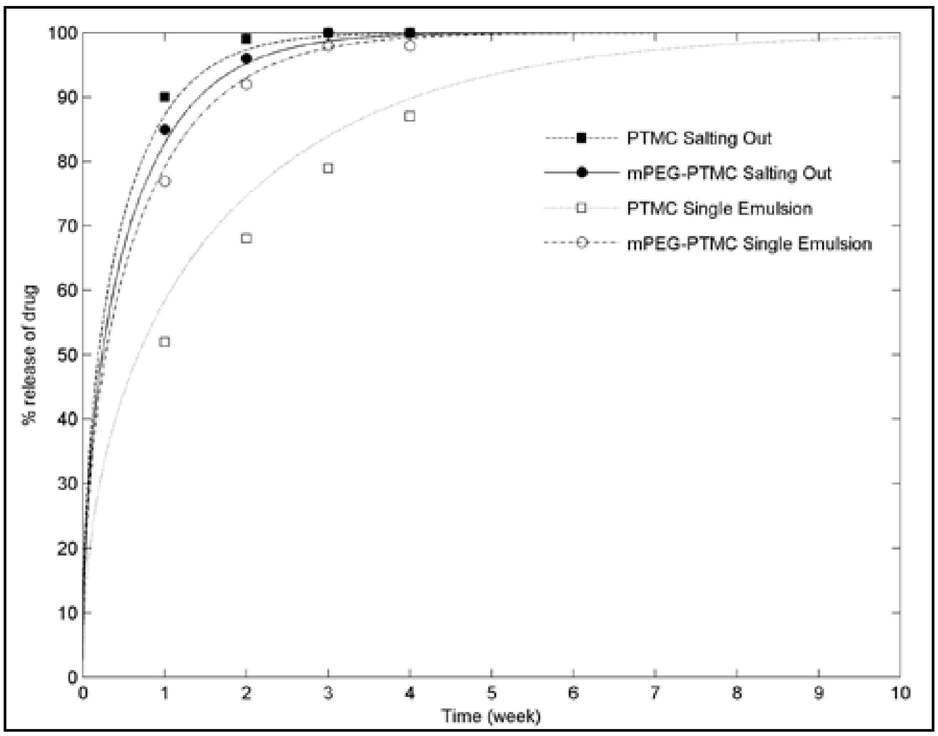


Figure 3. *Comparison between experimental and theoretical release profiles of dexamethasone from nanoparticles.*[25] *The profiles are obtained based on a diffusion coefficient of 22.6, 4.8, 12.7, and 4.8 × 10^{-18} cm^2/s for PTMC salting out, mPEG-PTMC salting out, PTMC single emulsion and mPEG-PTMC single emulsion, respectively. The corresponding average sizes of the nanoparticles used are 186, 95, 261, and 103 nm, respectively. The experimental drug release data for week 1, 2, 3, and 4 are estimated based on the published figure in the reference.*

Despite the difficulties faced by the teams in the MATLAB® component, most of the final reports illustrated correct trends in the drug concentration and release profiles with an acceptable degree of accuracy. Besides that, a handful of teams had written efficient MATLAB® codes that were capable of generating the required profiles in a short period of time. This certainly indicates that the contact sessions, the office and e-mail consultations, and the compilation of frequently asked questions have proven to be effective in guiding the teams in their project work.

The third section of the project turned out to be the weakest component among the teams. As it was an open-ended component, the quality of the work varied significantly among the various teams. There were some outstanding teams that were able to model experimental data by using published diffusion coefficients. An example is shown in Figure 3. While many of the teams provided innovative linkage or coupling of the knowledge gained from the earlier two sections of the project, a handful of teams had simply discussed the fabrication techniques without considering the drugs they had been assigned.

An online survey was conducted at the end of the course to gather project feedback and suggestions. Out of a class size of 246, 106 students took part in this voluntary survey and the results are summarized in Figures 4, 5, and 6. Most of the students perceived the design project as difficult when they first read the project description. Upon completion of the project, more students felt that the level of difficulty was normal rather than difficult (Figure 4). For the various components required in this project, more than 50% of the students found those that involved MATLAB® programming to be the most challenging (Figure 5). Not surprisingly, they also found contact sessions 2 and 3, during which MATLAB® programming was illustrated, to be the most useful resource (Figure 6).

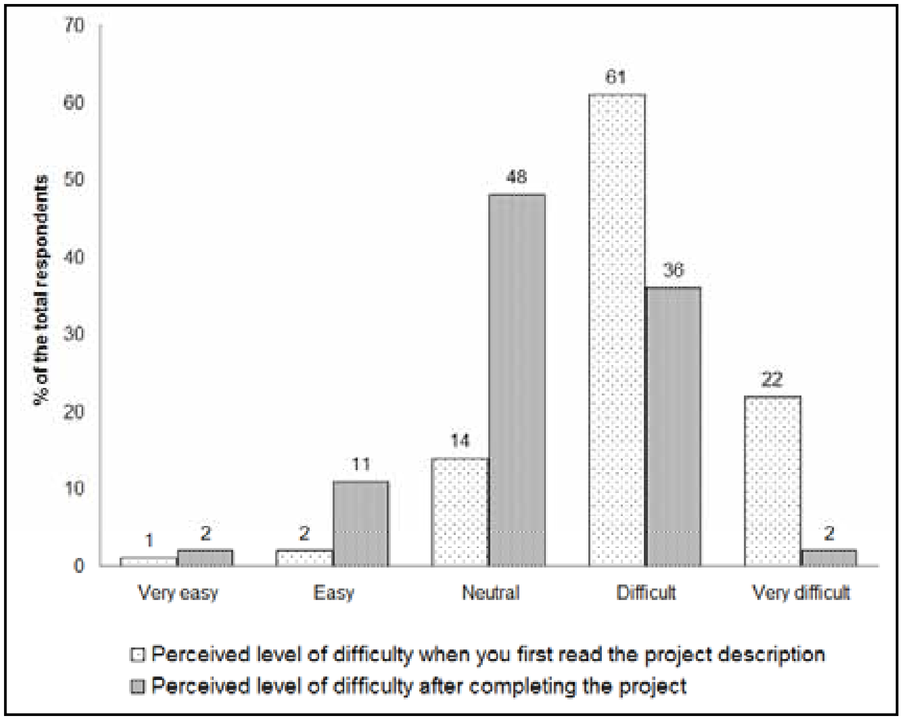


Figure 4. *Percentage of the total respondents selecting the perceived level of difficulty of the design project i) when the project description is first read, and ii) when the project is completed, based on a five-point Likert scale. The numbers displayed on top of the individual columns indicated the percentage of the total respondents selecting the particular option.*

CHALLENGES/LESSONS LEARNED

The main challenge of the project is that the students do not have prior knowledge about drug delivery systems. In addition, drug delivery is an emerging field, comprising a wide range of literature. Thus, it is essential to draw a proper framework for the scope of the project, simulate interest among students, and illustrate the importance of mass transfer in these drug delivery devices. Additionally, it is important for students to understand the various fabrication techniques of drug delivery devices before they embark on reviewing related literature materials. Due to the limitation of time and resources in the course, however, students are not able to get hands-on experiences with various fabrication techniques. One possible area for improvement is to conduct a laboratory tour where various fabrication techniques will be demonstrated on the spot. This will be complementary to the existing laboratory courses since these fabrication techniques are not currently covered.

Many of the students lacked the skills in translating a descriptive problem statement into a working MATLAB® code. Deciding on the amount of help to render the teams was not easy. On one hand, sufficient amount of help should be provided so that the teams would be able to start working on the project. On the other hand, too much guidance would be tantamount to spoon-feeding and would deprive the teams of a chance to learn from their mistakes. To overcome this situation, simple examples can be used as teaching materials to illustrate the problem and the solution, after which there should be time given for team trial and error before being advised by the student facilitators through consultations.

The open-ended component of the project was intended to allow room for creativity in responses from the various teams. Since the requirements were not clearly specified, questions about what type of areas to focus on were asked by many teams. In addition, the teams did not know the percentage of credit for the three sections of the project and thus, they were unsure of the amount of effort required for individual sections. The problem can be circumvented by informing teams upfront of the weightage of the individual components.

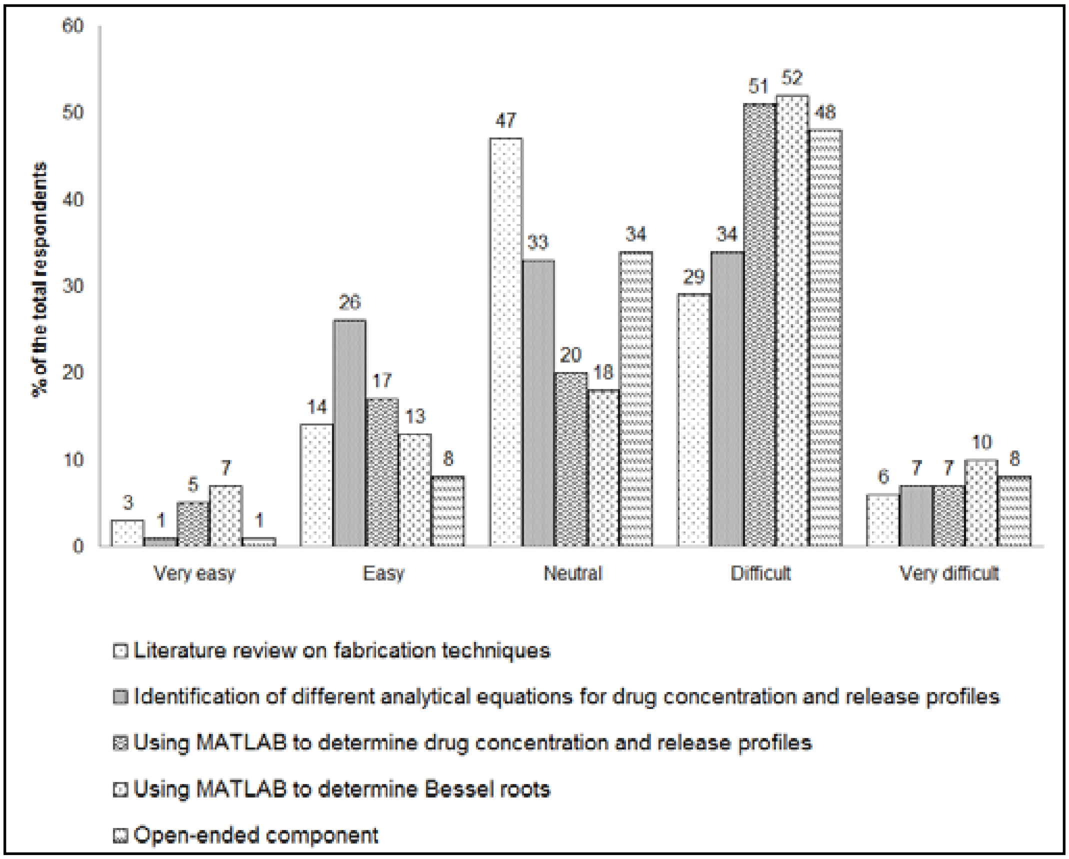
CONCLUSION

In the course of this project, the students have been assessed on the current techniques for the fabrication of drug delivery devices and the design of these delivery devices using MATLAB® software. Since this is the first time that the project is being implemented, there are many areas that can be further improved. This particular project can potentially serve as an interesting model for other mass transfer courses.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the Department of Chemical and Biomolecular Engineering,

Figure 5. Percentage of the total respondents selecting the perceived level of difficulty of the various components of the design project, namely i) literature review on fabrication techniques, ii) identification of different analytical equations for drug concentration and release profiles, iii) using MATLAB® to determine drug concentration and release profiles, iv) using MATLAB® to determine Bessel roots, and v) open-ended component, based on a five-point Likert scale. The numbers displayed on top of the individual columns indicate the percentage of the total respondents selecting the particular option.



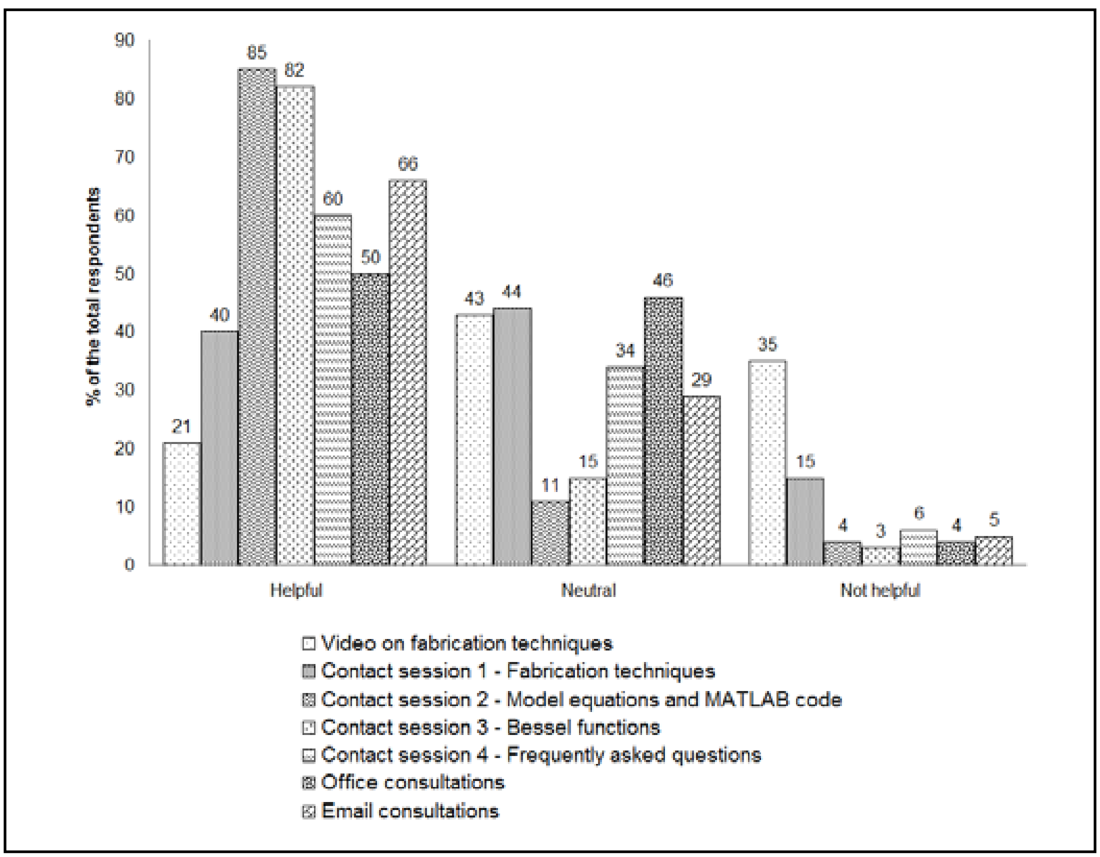


Figure 6. Percentage of the total respondents selecting the usefulness level of the various resources available for the design project, namely i) video on fabrication techniques, ii) four contact sessions, iii) office consultations, and iv) e-mail consultations, based on a three-point Likert scale. The numbers displayed on top of the individual columns indicate the percentage of the total respondents selecting the particular option.

National University of Singapore, under the grant number C-279-000-002-001. We also thank the technical support by Hao Qin, Chenlu Lei, Sudhir Hulikal Ranganath, Jian Qiao, Hemin Nie, Alireza Rezvanpour, and Dr. Wee Chuan Lim on various phases of this teaching project.

REFERENCES

1. "High Growth Reported for the U.S. Drug Delivery Systems Market," Reuters (2008); <http://www.reuters.com/article/idUS162213+11-Mar-2008+MW20080311>
2. Narasimhan, B., "Accurate Models in Controlled Drug Delivery Systems," in D.L. Wise (Ed.), *Handbook of Pharmaceutical Controlled Release Technology*, Marcel Dekker, Inc., New York (2000)
3. Farrell, S., and R.P. Hesketh, "An Introduction to Drug Delivery for Chemical Engineers," *Chem. Eng. Ed.*, **36**(3), 198 (2002)
4. Kaletunc, G., K. Duemmel, and C. Gecik, "Teaching Process Engineering Principles Using an Ice Cream Maker," *Chem. Eng. Ed.*, **41**(2), 131 (2007)
5. Condoret, J.S., "Teaching Transport Phenomena Around a Cup of Coffee," *Chem. Eng. Ed.*, **41**(2), 137 (2007)
6. Chen, X.D., "Cooking Potatoes: Experimentation and Mathematical Modeling," *Chem. Eng. Ed.*, **36**(1), 26 (2002)
7. Smart, J.L., "Optimum Cooking of French Fry-Shaped Potatoes: A Classroom Study of Heat and Mass Transfer," *Chem. Eng. Ed.*, **37**(2), 142 (2003)
8. Nollert, M.U., "An Easy Heat and Mass Transfer Experiment for Transport Phenomena," *Chem. Eng. Ed.*, **36**(1), 56 (2002)
9. Steidle, C.C., and K.J. Myers, "Demonstrating Simultaneous Heat and Mass Transfer with Microwave Drying," *Chem. Eng. Ed.*, **33**(1), 46 (1999)
10. Bevia, F.R., and M. Del Mar Olaya, "Mass Transfer Experiment: Determination of Liquid Diffusion Coefficients," *Chem. Eng. Ed.*, **36**(2), 156 (2002)
11. Nirdosh, I., L.J. Garred, and M.H.I. Baird, "Low-Cost Mass Transfer Experiments: Part 6. Determination of Vapor Diffusion Coefficient," *Chem. Eng. Ed.*, **34**(2), 158 (2000)
12. Kwon, K.C., T.H. Ibrahim, Y.K. Park, and C.M. Simmons, "Inexpensive and Simple Binary Molecular Diffusion Experiments," *Chem. Eng. Ed.*, **36**(1), 68 (2002)
13. Whitmire, D., and W. Blaylock, "A Simple Open-Ended Vapor Diffusion Experiment," *Chem. Eng. Ed.*, **38**(2), 122 (2004)
14. Robinson, K.K., J.S. Dranoff, C. Tomas, and S. Tummala, "Mass Transfer and Cell Growth Kinetics in a Bioreactor," *Chem. Eng. Ed.*, **36**(3), 216 (2002)
15. Magalhaes, F.D., and A. Mendes, "Single-Component Mass Transfer Across a Porous Membrane," *Chem. Eng. Ed.*, **32**(4), 286 (1998)
16. Mohammad, A.W., "Simple Mass Transfer Experiment Using Nanofiltration Membranes," *Chem. Eng. Ed.*, **34**(3), 264 (2000)
17. Freitas, S., H.P. Merkle, and B. Gander, "Microencapsulation by Solvent Extraction/Evaporation: Reviewing the State of the Art of Microsphere Preparation Process Technology," *J. Control. Release*, **102**(2), 313 (2005)
18. Govender, T., S. Stolnik, M.C. Garnett, L. Illum, and S.S. Davis, "PLGA Nanoparticles Prepared by Nanoprecipitation: Drug Loading and Release Studies of a Water Soluble Drug," *J. Control. Release*, **57**(2), 171 (1999)
19. Yu, Z., T.L. Rogers, J. Hu, K.P. Johnston, and R.O. Williams III, "Preparation and Characterization of Microparticles Containing Peptide Produced by a Novel Process: Spray Freezing into Liquid," *Eur. J. Pharm. Biopharm.*, **54**(2), 221 (2002)
20. Wang, F.J., and C.H. Wang, "Effects of Fabrication Conditions on the Characteristics of Etanidazole Spray-Dried Microspheres," *J. Microencapsul.*, **19**(4), 495 (2002)
21. Xie, J., J.C.M. Marijnissen, and C.H. Wang, "Microparticles Developed by Electrohydrodynamic Atomization for the Local Delivery of Anticancer Drug to Treat C6 Glioma in Vitro," *Biomaterials*, **27**(17), 3321 (2006)
22. Lee, L.Y., C.H. Wang, and K.A. Smith, "Supercritical Antisolvent Production of Biodegradable Micro- and Nanoparticles for Controlled Delivery of Paclitaxel," *J. Control. Release*, **125**(2), 96 (2008)
23. Crank, J., *The Mathematics of Diffusion*, Clarendon Press, Oxford (1975)
24. Ritger, P.L., and N.A. Peppas, "A Simple Equation for Description of Solute Release I. Fickian and Non-Fickian Release from Non-Swellable Devices in the Form of Slabs, Spheres, Cylinders or Discs," *J. Control. Release*, **5**(1), 23 (1987)
25. Zhang, Z., D.W. Grijpma, and J. Feijen, "Poly(Trimethylene Carbonate) and Monomethoxy Poly(Ethylene Glycol)-Block-Poly(Trimethylene Carbonate) Nanoparticles for the Controlled Release of Dexamethasone," *J. Control. Release*, **111**(3), 263 (2006) ❒

"Ideas to Consider," ***continued from page 317***

135. Markkula Center for Applied Ethics. Ethical Decision Making, Santa Clara University, <http://www.scu.edu/ethics/practicing/decision/>, accessed April 2010
136. Pritchard, M., Center for the Study of Ethics in Society. Teaching Engineering Ethics: A Case Study Approach. <http://ethics.tamu.edu/pritchar/an-intro.htm>, accessed April 2010
137. Environmental Protection Agency. Exposure Assessment Tools and Models. <http://www.epa.gov/oppt/exposure/pubs/episuitedl.htm>, accessed April 2010
138. Miller, R., Estimating Capital Costs. <http://inside.mines.edu/fs_home/rlmiller/capcosts.pdf>, accessed April 2010
139. Milligan, D.A., Process Equipment Cost Estimates. <http://www.matche.com/EquipCost/index.htm>, accessed April 2010
140. University of Texas at Austin. Chemical Engineering Economics. <http://www.lib.utexas.edu/chem/info/chemengecon.html>, accessed April 2010
141. University Program. Aspen Tech. <http://www.aspentech.com/corporate/university/products.cfm>, accessed April 2010
142. Myers and Briggs Foundation. My MBTI Personality Type. <http://www.myersbriggs.org/>, accessed April 2010
143. Felder, R., Index of Learning Styles. <http://www4.ncsu.edu/unity/lockers/users/f/felder/public/ILSpage.html>, accessed April 2010
144. Sauer, S., and P. Arce, "Team Member Selection: A Functional-Based Approach," *Proceedings* of the 2004 Annual Conference and Exposition, ASEE (2004)
145. Ekwaro-Osire, S., and P. Orono, "Design Notebooks as Indicators of Student Participation in Team Activities," *Proceedings* of 2007 Frontiers in Education Conference, Milwaukee, WI, 1348-53 (2007)
146. Turnitin, #1 Plagiarism Checker to Ensure Academic Integrity, <http://turnitin.com>, accessed April 2010
147. Ohland, M.W., M.L. Loughry, R.L. Carter, L.G. Bullard, R.M. Felder, C.J. Finelli, R.A. Layton, and D.G. Schmucker, "The Comprehensive Assessment of Team Member Effectiveness: A New Peer Evaluation Instrument," *Proceedings* of the 2006 Annual Conference & Exposition, ASEE (2006)
148. Comprehensive Assessment of Team Member Effectiveness. <https://engineering.purdue.edu/CATME/index.htm>, accessed April 2010
149. Cadwell, K., G. Zenner, N. Chesler, and W. Crone, "Developing Undergraduate Students' Design Skills Using On-Line Video Modules and Active-Learning Exercises," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
150. Interdisciplinary Education Group. Research and Design Skills. <http://www.mrsec.wisc.edu/Edetc/research/#des>, accessed April 2010
151. Thomas Net. Thomas Register. <http://www4.thomasregister.com>, accessed April 2010
152. Bullard, L.G., P.K. Niehues, S.W. Peretti, and S.H. White, "Web-based Delivery of Chemical Engineering Design Projects," *Chem. Eng. Ed.*, **39**(3), 194 (2005) ❒

AN UNDERGRADUATE COURSE IN MODELING AND SIMULATION OF MULTIPHYSICS SYSTEMS

Estanislao Ortiz-Rodriguez, Jorge Vazquez-Arenas, and Luis A. Ricardez-Sandoval
University of Waterloo • Waterloo, Ont., Canada N2L 3G1

A mathematical model is an abstraction of a physical system, *i.e.*, a mathematical image of the reality. These models are of great importance in engineering because they can provide relevant information about the system being modeled which may not be available from experiments, *e.g.*, a model can explain variations in the measurable macroscopic properties of a physical system using accurate information from the microscopic level, which cannot usually be measured in a laboratory. Also, mathematical models help engineers to make decisions and to improve the quality of a process. On the other hand, mathematical models can lead to wrong decisions or conclusions about the system under study if they are not validated with experimental work. Therefore, a complete study of a physical system should integrate modeling, simulation, and experimental work.

The process modeling fundamentals are usually introduced to engineering students in one or two courses on transport phenomena. Although there are textbooks available in the field of transport phenomena,[1-5] most of them present the momentum, energy, and mass transport phenomena as independent subjects. This limits the application of the concepts learned in transport phenomena courses to practical systems where different laws of physics may occur simultaneously, *e.g.*, the unsteady mass transport of a chemical flowing, with a given velocity profile, through a non-isothermal tubular reactor with an asymmetric geometry. It has been widely recognized that the study of fluid dynamics, heat, and mass transfer in a unified framework constitutes one of the keystones in fundamental engineering sciences and contributes to the development of new emerging fields in engineering such as nanotechnology.[1,6] Therefore, it is important to expose undergraduate engineering students to the modeling and simulation of physical processes that involve the study of two or more laws of physics; this has been referred to as multiphysics modeling.

***Estanislao Ortiz-Rodriguez** holds B.Sc. and M.Sc. degrees in chemical engineering from the Autonomous University of San Luis Potosi (UASLP), in Mexico. He has worked in the chemical industry sector in Mexico, where he has gained experience in processing operations such as crystallization and drying of inorganic compounds. Recently, he was awarded a Ph.D. degree in chemical engineering from the University of Waterloo, in Canada. Through his graduate programs, the author has specialized in polymer characterization and polymer processing. In this latter topic, he has implemented numerical simulations to address conventional and reactive extrusion operations in twin screw extruders.*

***Luis A. Ricardez-Sandoval** received his B.Sc. degree from the Instituto Tecnologico de Orizaba in Orizaba, Mexico. He obtained his M.Sc. degree from the Instituto Tecnologico de Celaya in Celaya, Mexico. He received his Ph.D. degree from the University of Waterloo in Waterloo, Canada. Prior to joining the graduate program at UW, Luis worked in the manufacturing and oil and gas industry for several years. He is currently an assistant professor in the Chemical Engineering Department at the University of Waterloo. His current research interests include multiscale modeling of chemical processes, design and control of dynamic systems, systems identification, and robust control.*

***Jorge Vazquez-Arenas** received his B.Sc. in chemical engineering from the Minatitlan Institute of Technology (ITM Mexico, 2003), his M.Eng. in Minerals Engineering from the Autonomous University of San Luis (UASLP Mexico, 2005), and he is currently a Ph.D. candidate in the Department of Chemical Engineering at the University of Waterloo. He was a two-year (UAM Mexico, 2007) research fellow in the department of Chemistry in the Metropolitan Autonomous University. His research and educational interests focus in the modeling of electrochemical systems, electrodeposition of single metals and alloys, hydrometallurgy, corrosion, passivation, and EIS methods.*

The multiphysics modeling of a physical process may involve not only the simultaneous solution of different laws of physics occurring at the same time but also the coupling of two or more phenomena occurring at different length or time scales. The latter class of systems, also referred to as multiscale systems, are of increasing interest in engineering since they can be used to describe the macroscopic properties of a physical system by modeling and simulating the microscopic behavior of the physical process.[7,8] Although a sound background in numerical techniques may be desirable for simulating the type of processes previously described, the use of commercial software may prove very valuable for accomplishing this task, especially for those who are just becoming familiar with the subject of modeling and simulation.

In the Fall of 2008, the Micro and Nano Systems Computer-Aided Design (CAD) course, NE-336, was offered for the first time to the third-year students of the nanotechnology undergraduate program at the University of Waterloo. The goal of this course is to study the process modeling fundamentals and to train students in the modeling and simulation of multiphysics models that are relevant in the field of nanotechnology. Also, the students are exposed to conventional numerical techniques available for solving both ordinary and partial differential equations (ODEs and PDEs, respectively). Since the course deals with the modeling and simulation of micro and nano systems, one of the most important goals of the course is to train students in the implementation of multiphysics models. For this purpose, they have to perform different computational laboratories that provide them with practical hands-on experience in the simulation of micro systems. These laboratories are intended to provide a clear physical understanding of the systems being simulated. Since the course is mainly focused on the modeling and numerical simulation of multiphysics systems, only introductions to the electronic and atomistic simulations required to model nano systems are discussed by the instructor in the last section of the course (see course structure in section 2.1). The goal of this paper is to give a general overview of the NE-336 course and to present one of the computational laboratories covered in the course. The laboratory presented in this work corresponds to a drug delivery system where the macroscopic properties of the system depend upon the variations at the microscopic system level.

The rest of this paper is organized as follows: in section 2, an overview of the NE-336 course is presented. Section 3 presents a computational laboratory that addresses the release of a drug in a storage tank. The mathematical model used to describe the behavior of this system, the challenges posed by this problem, and the laboratory tasks performed by the students on this lab are discussed in this section. Section 4 presents the evaluation made by the students regarding the learning experience in this course. Concluding remarks are presented in section 5.

2. COURSE DESCRIPTION

Micro and Nano Systems Computer-Aided Design is one of the core courses in the Nanotechnology Engineering curriculum at the University of Waterloo. This course, NE- 336, is composed of three weekly hours of lecture, one weekly hour of tutorial, and three biweekly hours of computational laboratory. Lectures are used by the course instructor to provide the essential course material. Tutorial sessions are used to reinforce the concepts presented in the lectures, to solve sample problems, and as a pre-laboratory session. Laboratory sessions are used to help students to gain practical experience in the implementation of multiphysics models in an application software, on its simulation, and on the analysis of the simulation results. The course grading is based upon a midterm exam, laboratory reports and assignments, handwritten quizzes, a laboratory quiz, and a final exam that covers the complete course content. The course is suitable for those students who are already familiar with classical thermodynamics and the traditional analytical methods for solving ODEs and PDEs.

The course objectives can be summarized as follows:

i) Teach how to derive first-principle models for simple physical systems that involve fluid dynamics, heat, and mass transfer.

ii) Present the basic numerical techniques available to solve ODEs and PDEs.

iii) Train the students in the use of COMSOL, a widely used commercial software based in Finite Element Analysis (FEA).

iv) Stress the multiphysics nature of real systems and highlight the complexity of the solutions of multiphysics models describing specific micro and nano systems.

v) Solve illustrative case studies where the coupling between different mathematical models is implemented.

2.1 Course Structure

Based on the learning goals specified for this course, the course content has been divided as follows:

i) **Physics modeling process.** *This section covers first-principle modeling and empirical modeling. Here, the basic concepts used to model physical systems that follow the laws of classical mechanics (*i.e.*, conservation of mass, energy, and momentum) are applied to simple physical systems. The basic steps in the modeling process, the different approaches used to obtain a first-principle model, and the traditional methods used to perform empirical modeling are discussed. Each of the above topics is supported with practical examples,* e.g.*, cooling of a fluid flowing through a circular section of a tube, analysis of a plug flow reactor, and flow in a circular tube. The books by Bird, et al.,[1] and Tosun[3] are the basic sources for this section of the course.*

ii) **Numerical methods for solving ODEs and PDEs.** *This section presents the traditional numerical* *methods available to solve initial value problems, such as Euler and Runge-Kutta methods, boundary value problems, the shooting method, and eigen-value problems for solving ODEs. Similarly, methods used in the solution of PDEs like the finite difference method, the method of lines, and an introduction to the finite element method, are discussed. In this section of the course, a detailed discussion on truncation and discretization errors in numerical analysis is presented. For example, students are made aware of the errors generated by the use of approximate functions in the different terms of the PDEs containing the variable to be solved. Here, it is also shown that the errors depend on several factors, such as the truncation of Taylor series to form a particular finite difference scheme,* e.g., *first and second order, the order of a Lagrange polynomial to form a shape function in finite element analysis, and the size of the mesh elements. Also, comparisons between analytical solutions and those obtained by finite difference methods,* i.e., *forward, backward, and centered finite difference, are discussed in the course. Moreover, comparisons between finite element and finite difference methods for regular and irregular geometries are also discussed on this part of the course.*

Furthermore, a grid convergence analysis is evaluated by solving a particular system using different grid sizes. From this analysis, the students realize that meshing the domain of the physical system is a key step in the numerical set-up of the problem that has a direct effect on the numerical solution. A formal grid convergence analysis that involves the use of relatively complex and time-consuming algorithms to deal with stiff multiphysics systems is beyond the scope of this undergraduate course. The basic references for this part of the course are Chapra and Canale[9] and Chadrupatla and Belegundu.[10]

iii) **Introduction to multiphysics models.** *The goal of this section is to expose students to physical systems that can be modeled using two or more laws of physics (multiphysics approach) and to train them in the implementation of such models in the application package used in the course,* i.e., *COMSOL. The examples provided in this section span from the modeling of the Joule heating effect in a section of a pipeline to the modeling of the mass transport of an incompressible fluid in a non-isothermal reactor. Other illustrative examples are used by the course instructor to show the importance of sensitivity analysis and the effect of parameter uncertainty on the simulation results. Most of the topics presented in this section are taken from Zimmerman,[6] Bird, et al.,[1] Tosun,[3] and the COMSOL library.[11]*

iv) **Advanced topics in multiphysics models.** *The last part of the course is used to model physical systems where the coupling between the different mathematical equations appears at one boundary condition,* i.e., *extended multiphysics systems. Also, the implementation of multiphysics models with periodic boundary conditions is discussed. Likewise, this last section of the course is used to introduce the students to the traditional methods used in the modeling of systems at the atomistic, molecular, and coarse-grained level. This section of the course is supported with the COMSOL library,[11] Zimmerman,[6] and Hung, et al.[7]*

2.2 Computational Laboratories

The computational laboratories are a key component of the NE-336 course. In the laboratory sessions, the students are able to use MATLAB and COMSOL, which are the application packages used in this course. The first of these software packages is primarily used to solve those systems that can be modeled using ODEs, whereas the second one is used to model physical systems that involve PDEs or a combination or PDEs with ODEs (see case study in Section 3).

The first laboratory session, laboratory zero, presents the students with an overview of the laboratories to be performed throughout the course. During this session, the course instructor implements, simulates, and analyzes two simple models on each application package. The model implemented in MATLAB corresponds to a simple non-isothermal mixing tank process modeled using two ODEs, whereas the model implemented in COMSOL describes the unsteady Joule heating effect of a micro-resistor beam. The learning goals of the first and the second laboratories are to introduce the students to both of the application packages used in the course. In the first laboratory, the students learn the basic syntax required to execute ODEs in MATLAB, whereas in the second laboratory they learn the basic steps in the modeling process in COMSOL. For these laboratories, the physics of the models implemented on each application package are relatively simple. The third laboratory addresses the implementation of a drug delivery model in COMSOL, which is presented in the next section. The fourth and the fifth laboratories cover an electro-migration model and a micro cantilever beam model, respectively. These models require the application of different laws of physics that make the problem challenging to the students. The last laboratory session of the term, a laboratory quiz, is used to evaluate the students in their ability to implement models in both application packages. This quiz is of great significance for this course since it evaluates the abilities and skills learned by the students in the laboratory sessions.

Each of the laboratory manuals is divided in three sections: Section 1 contains a brief introduction of the physical system to be studied as well as the most significant aspects of its implementation in the corresponding application package. Section 2 covers basic questions regarding the implementation of the model. Section 3 lists questions that require additional simulations of the model, model analysis and parametric sensitivity analysis. The students must submit at the end of the laboratory session their responses to Section 2. This portion of the laboratory is used to evaluate the student's performance on the laboratory. Section 3 of the laboratory manual is submitted by the students a week after the laboratory session is completed. This is because the questions posed on this section require an in-depth analysis of the model and additional computational simulations. This portion of the laboratory (Section 3) is considered as an assignment for the course.

3. CASE STUDY: DRUG RELEASE IN A BATCH PROCESS

This computational laboratory deals with the transient release of a drug in a mixing storage tank. The learning objective of this computational experiment is to show the students the modeling and simulation of a system described by an ODE coupled with a PDE at one of the boundary conditions. This kind of mathematical modeling, also referred to as extended multiphysics problems, is very common in chemical processes where the multiple scale modeling of the physical phenomena occurs.[6] The physical description of the process is shown in Figure 1. The system sketched on this figure is widely used to study the drug release kinetics in biological systems (Tan, *et al*.[12,13]). The drug is placed into a drug reservoir, assumed to be a solid sphere of radius δ, which is encapsulated by a polymer substance, *e.g*., a nano-gel. The encapsulating layer is used to control the drug delivery rate. As shown in Figure 1, the nano-particle, *i.e*., the nano-gel and the drug reservoir, are assumed to form a solid sphere of radius R. A mixing storage tank is assumed to be filled with a large number of nano-particles, Np. The tank is used to mimic the drug concentration profiles in a given system, *e.g*., a human body. The system is assumed to be isothermal and well stirred. Also, the density of the fluid, *i.e*., the fluid on the side of the tank, is considered to be constant.

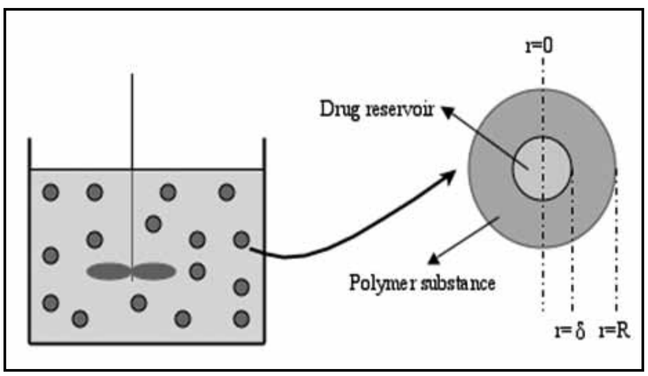


Figure 1. *Physical system.*

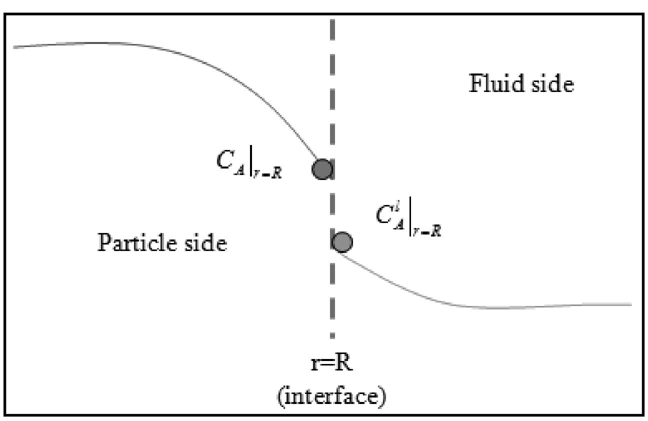


Figure 2. *Coupling of the macro and the nano systems.*

Due to the educational nature of the present laboratory, several simplifications were made regarding some other considerations that can be involved when dealing with the modeling of a drug delivery system. The drug particles are considered to be appropriately described by an average particle behavior regarding their mass transport properties. That is, classical continuum transport equations are assumed to apply to the presented drug delivery system, which is composed of both the drug particles and the fluid inside the tank. In principle, atomistic dynamic simulations may be required to model the dynamic behavior of each particle in the system. These simulations, however, may be lengthy and may increase the complexity of the present educational laboratory. Since the objective of this computational laboratory is to present the modeling and simulation of an extended multiphysics system such as the drug release problem, molecular simulations of the drug particles are outside the scope of the present laboratory. Moreover, in a more realistic scenario the drug reservoir may consist of a polymeric matrix that can experience swelling and erosion.[14,15] Further, a constant drug release rate may be sought if the solution inside the drug reservoir is oversaturated (since the maximum concentration of drug should be constant and correspond to the saturation concentration[14]).

The transport of the drug through the drug reservoir and the polymeric material is controlled by the unsteady diffusion within the sphere. This diffusion process is mathematically described as follows (microscopic model):

$$r^2 \frac{\partial C_A}{\partial t} = D \frac{\partial}{\partial r}\left(r^2 \frac{\partial C_A}{\partial r} \right) \tag{1}$$

where C_A is the drug concentration in the nano-particle (mol/m^3); r, the radius of the solid sphere (m); and D is the diffusion coefficient (m^2/s) in either layer one (D_r) or layer two (D_p). The boundary conditions (BCs) and the initial condition (IC) assumed for this microscopic process are as follows:

- BC1: at r=0, C_A is finite, *i.e*., $\frac{\partial C_A}{\partial r} = 0$
- BC2: at r=δ, $-D_r \frac{\partial C_A}{\partial r}\Big|_{r=\delta} = -D_p \frac{\partial C_A}{\partial r}\Big|_{r=\delta}$
- BC3: at r=R, $-D_p \frac{\partial C_A}{\partial r}\Big|_{r=R} = k_c \left(C_A^l\big|_{r=R} - C_A^\infty \right)$
- IC: at t=0, $C_A = C_{A0}$

where the term k_c represents the mass transfer coefficient (m/s) which accounts for the diffusion on the fluid side; $C_A^l\big|_{r=R}$ is the drug concentration on the surface of the sphere on the fluid side; C_A^∞ is the concentration of the drug in the tank, *i.e.*, a point in the tank that is assumed to be far away from the surface of the particle; and C_{A0} is the initial drug concentration in the drug reservoir.

Figure 2 shows the interface between the surface of the nano-particle and the fluid. As shown, it is evident that a relationship must be given to relate the interfacial compositions $C_A^l\big|_{r=R}$ and $C_A\big|_{r=R}$. One alternative is to assume equilibrium across the interface, that is,

$$C_A^l\Big|_{r=R} = KC_A\Big|_{r=R} \qquad (2)$$

where K represents an equilibrium constant. The unsteady drug concentration in the mixing tank is defined as follows (macroscopic model):

$$V\frac{dC_A^\infty}{dt} = NpA_p kc\left(C_A^l\Big|_{r=R} - C_A^\infty\right) \qquad (3)$$

where V is the tank's volume (m^3) and A_p is surface area of the particles (m^2). The initial concentration of the drug in the tank is assumed to be zero.

The present educational laboratory presents the students with the challenge of coupling the drug transport in the nano-particle and its distribution in the storage tank. This is because the drug concentration in the bulk depends on the drug's concentration at the surface of the nano-particle. Thus, the students must solve a PDE [Eq. (1)] and an ODE [Eq. (3)] simultaneously. Since the coupling between the drug transport in the nano-particle and the concentration of the drug in the bulk occurs at the surface of the nano-particle (BC3), this case study is considered to be an extended multiphysics problem.[16] The solution of this system of equations [Eqs. (1) and (3)] requires the implementation of numerical techniques. Thus, this type of problem is suitable to exemplify the capabilities of COMSOL in solving practical engineering problems.

The proposed model is built-up in COMSOL in two sequential steps. First, only the drug's transport in the nano-particle is modeled according to Eq. (1) without considering the coupling of this equation with Eq. (3), *i.e.*, C_A^∞ is assumed to be negligible [C_A^∞=0 in Eq. (3)]. For this laboratory, the students use the 2-D unsteady mass transport by diffusion module in COMSOL[11] to account for the transient behavior of the drug concentration throughout the nano-particle, described by Eq. (1). It is important to mention that Eq. (1) can also be implemented using a 1-D model given the symmetry of the sphere. In this laboratory, however, the choice of using a 2-D model is made because the step-up of this type of model is simpler than the one corresponding to a 1-D model, especially given the two different materials of which the nano-particle is composed. Also, when implementing a 2-D model, the variation of the drug concentration can be obtained for a complete cross section of the sphere, giving a clear physical meaning of the variation of the drug concentration in the sphere at specific times. A representative solution for the first part of the laboratory is the drug concentration profile as a function of the radius of the nano-particle for different times ranging from 600 to 1000 s (Figure 3). As shown in this figure, there are two different profiles (for each fixed time value) in the nano-particle. One profile corresponds to the diffusion of the drug inside the drug's reservoir and the other corresponds to the diffusion of the drug through the nano-gel. From this plot, the students can observe that different nano-gel and drugs' reservoir materials will have an effect on the drugs' diffusion rate. Thus, in the actual computational laboratory, the students are requested to test this model using different drugs' reservoirs and nano-gel materials.

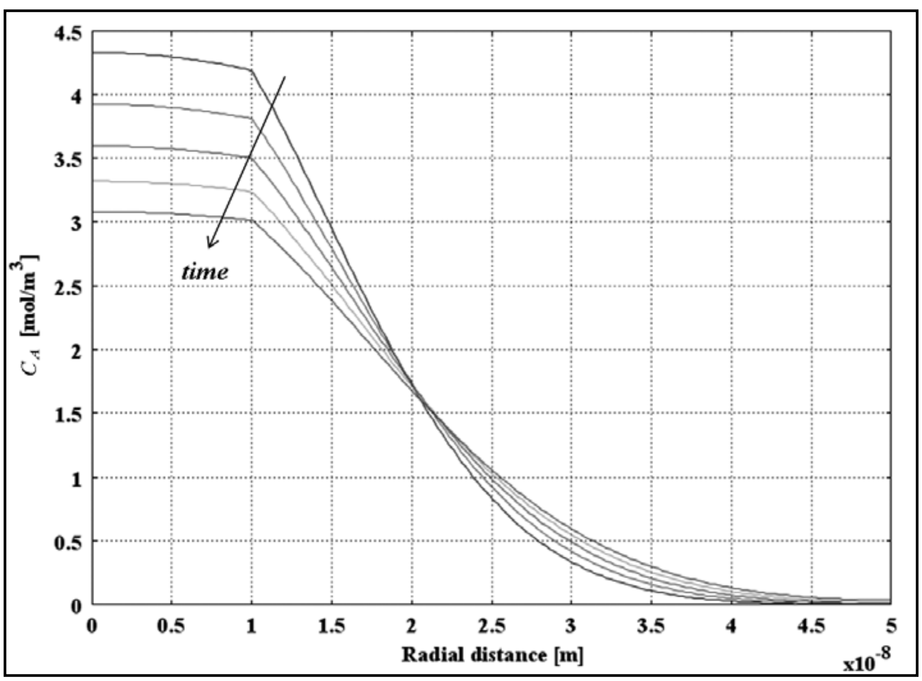


Figure 3. *Concentration profile in the nano-particle, C_A, for different times from 600 – 1000 s.*

Once the nano-particle model has been implemented, the second step in the modeling process consists of coupling the diffusion model with the variations of the drug in the storage tank described by Eq. (3) (macroscopic model). The 1-D PDE coefficient form module in COMSOL[11] was used to represent the macroscopic ODE model. Thus, a single line of arbitrary length is used to represent the variation of the drug concentration in the storage tank [Eq. (3)]. Since the coupling between the microscopic model [Eq. (1)] and the macroscopic model [Eq. (3)] occurs at one boundary condition (BC3), the line representing the storage tank's model must intersect with the external surface of the nano-particle, *i.e.*, at r=R. Then, the variable that represents the drug concentration at the surface on the nano-particle side is made available in the 1-D macroscopic model using the variable extrusion option in COMSOL.[11] This is the most challenging part in the implementation of this model in COMSOL. The laboratory manual includes hints in this section to assist the students with the coupling of the microscopic and the macroscopic model. Also, the students can seek help from the laboratory assistants. Once the drug-release model has been completely implemented, the students are requested to simulate this process under different scenarios. The base case scenario assumes that the concentration of the drug at the radius of the nano-particle is the same on both the fluid and the nano-particle sides, *i.e.*, K=1 in Eq. (2). Figure 4 shows the time evolution of the drug concentration in the storage tank for this scenario. At the end of the laboratory session the students must submit a plot like that shown in Figure 4. The rest of the scenarios considered in the laboratory were designed to provide an in-depth knowledge of the drug delivery process. This includes a parametric analysis on the effect of using different materials for the encapsulating layer and a study on the effect of the thickness of the nano-gel layer on the drug's delivery rate. Since these tasks require an in-depth analysis, they are submitted one week after the laboratory was performed and are considered as assignments in the course.

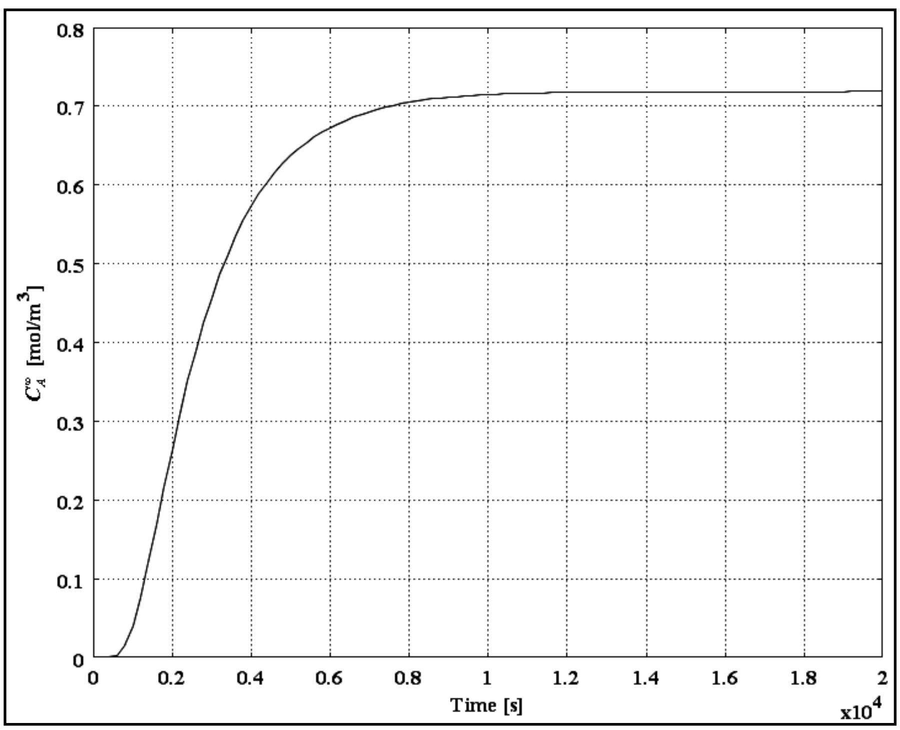


Figure 4. *Time-dependent profile of the drug concentration in the tank,* C_A^∞.

4. ASSESSMENT AND FEEDBACK

At the end of the term, a survey designed by the Faculty of Engineering of the University of Waterloo was conducted with students who were enrolled in the NE-336 course. The objective of the survey is to provide instructors with feedback as to how the teaching methods and skills were received by the students. From the responses of the survey, there was a clear consensus that the new skills learned in this course will be relevant to the future careers of the students and that the course introduced them to a new aspect of engineering: modeling and simulation. Also, the students could immediately realize how the recently acquired knowledge could be applied to their careers as engineers. A follow-up on a few of the students who were enrolled in this course indicated that some of them are currently applying the skills and subjects learned in this course to perform their fourth-year projects and in their co-operative terms (work internships).

Although students expressed appreciation of the hands-on experience provided by the computational laboratories, some of them also considered that the laboratory tasks were lengthy. This aspect coincides with the evaluation of the course where the required course workload was unfavorably evaluated by the students, in contrast with a very positive evaluation of the assignment contribution. Some students also expressed that more time could be spent in class explaining the systems to be simulated in the computational laboratories. These valuable comments from the students have been taken into consideration to improve the design and the learning experience for nanotechnology students who will take this course in the future. Some relevant comments expressed by the students in the survey are the following:

Student 1: *"I think the best aspect of the course content was the numerical PDE/ODE section, because it provides the mathematical foundation for doing any computational mathematics."*

Student 2: *"I think this was a vital course to have in undergraduate education, especially in engineering or applied science. Most of the mathematics tackled by us are not analytical, but numerical. This course provides the toolkit to approach such applied math problems."*

5. CONCLUDING REMARKS

A general overview on the modeling and simulation course offered in the nanotechnology engineering undergraduate program at the University of Waterloo was presented. The aim of this course is to make nanotechnology engineering students familiar with the modeling and simulation of physical systems that involve the multiphysics nature of most of the processes relevant in engineering. To achieve this task, students must complete a series of computational laboratories that cover the implementation of multiphysics models in a suitable educational software package such as COMSOL. A computational laboratory that addresses the implementation of a relatively simple drug-release model was presented. The goal of this laboratory is to train the students in the implementation of extended multiphysics systems and to show that the microscopic behavior of a process has a direct effect on the macroscopic measurable properties of the system. Many of the students who took this course in Fall 2008 are currently applying the tools learned in the course in their fourth-year projects and in their work-term internships. This confirms that the learning goals specified for this course were accomplished and that the modeling and simulation of multiphysics systems is an essential component in the curriculum of the nanotechnology engineering students.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Chemical Engineering Department at the University of Waterloo, NSERC, and CONACYT for their financial support.

REFERENCES

1. Bird, R.B., W.E Stewart, and E.N. Lightfoot, *Transport Phenomena*, 2nd Ed., Wiley (2007)
2. Welty, J.R., C.E. Wicks, R.E. Wilson, and G.L. Rorrer, *Fundamentals of Momentum, Heat, and Mass Transfer*, 5th Ed., Wiley (2008)
3. Tosun, I., *Modeling in Transport Phenomena A Conceptual Approach*, 2nd Ed., Elsevier (2007)
4. Whitaker, S, *Introduction to Fluid Mechanics*, Krieger Pub. Co. (1992)
5. Slattery, J.C., *Advanced Transport Phenomena*, Cambridge University Press (1999)
6. Zimmerman, W.B.J., ed., *Multiphysics Modeling with Finite Element Methods*, World Scientific (2006)
7. Hung, F.R., K.E. Gubbins, and S. Franzen, "A Graduate Course on Multi-Scale Modelling of Soft Matter," *Chem. Eng. Ed.*, **38**, 242 (2004)
8. Wood, B.D., "Taylor-Aris Dispersion An Explicit Example for Understanding Multiscale Analysis via Volume Averaging," *Chem. Eng. Ed.*, **43**, 29 (2009)
9. Chapra, S.C., and R.P. Canale, *Numerical Methods for Engineers*, 5th Ed., McGraw-Hill (2006)
10. Chandrupatla, T.R., and A.D. Belegundu, *Introduction to Finite Elements Methods in Engineering*, 3rd Ed., Prentice Hall (2002)
11. COMSOL Multiphysics®, Version 3.5a, documentation manuals (2008)
12. Tan, J.P.K., C.H. Goh, and K.C. Tam, "Comparative Drug Release Studies of Two Cationic Drugs From pH-Responsive Nanogels," *Eur. J. Pharm. Sci.*, **32**, 340 (2007)
13. Tan, J.P.K., A.Q.F. Zeng, C.C. Chang, and K.C. Tam, "Release Kinetics of Procaine Hydrochloride (PrHy) from pH-Responsive Nanogels: Theory and Experiments," *Int. J. Pharm.*, **357**, 305 (2008)
14. Siepmann, J., and F. Siepmann, "Mathematical Modeling of Drug Delivery," *Int. J. Pharm.*, **364**, 328 (2008)
15. Blagoeva, R., and A. Nedev, "A Problem for Drug Release From 2-D Polymeric Systems," *Mechanistic Res. Comm.*, **35**, 344 (2008)
16. Zimmerman, W.B.J., P.O. Mchedlov-Petrossyan, and G.A. Khomenko, "Extended Multiphysics" in *Multiphysics Modeling with Finite Element Methods*, ed. Zimmerman, W.B.J., World Scientific (2006) ❐

IDEAS TO CONSIDER FOR NEW CHEMICAL ENGINEERING EDUCATORS: PART 2
(Courses Offered Later in the Curriculum)

JASON M. KEITH
Michigan Technological University • Houghton, MI 49931-1295
DAVID L. SILVERSTEIN
University of Kentucky • Paducah, KY 40506-0046
DONALD P. VISCO, JR.
Tennessee Technological University • Cookeville, TN 38505
LISA G. BULLARD
North Carolina State University • Raleigh, NC 27695-7905

Although teaching is a critical mission of any college or university, the heightened research aspirations of many institutions necessitate that faculty members spend less time on instructional activities, at least if that new professor wants to exceed the research standards set for tenure and promotion. Thus, when a faculty member is tasked with teaching a new course, developing a good set of instructional materials can be a challenging, time-consuming task. In this paper we review some of what we consider the best practices in engineering education applied to the following courses: solution thermodynamics; heat and mass transfer; kinetics and reactor design; process control; and senior design.

We note that this work was first presented at the 2007 ASEE Summer School[1] and published in the 2009 ASEE conference proceedings as paper #AC 2009-29,[2] although updated here to reflect more recent works. Also, note that a companion paper that covers those chemical engineering classes that normally occur earlier in the curriculum (freshmen chemical engineering; material and energy balances; fluid mechanics; introductory thermodynamics; and separations) was presented at the 2007 ASEE Summer School[3] and is published in the 2008 ASEE Annual Meeting as paper #AC 2008-1147,[4] the 2008 AIChE conference proceedings,[5] and within the Summer 2009 issue of *Chemical Engineering Education*.[6] Furthermore, the reader may be interested in viewing recorded oral presentations from the 2008 AIChE Centennial Topical Conference on Education for these and other core chemical engineering subjects at the AIChE Education Division website.[7]

The format used for each course is:

- *Brief description of typical course scope*
- *Discussion about novel and successful methods used, including best practices and new ideas*
- *Listing of "toughest concepts" for the students (and suggestions on how to address them)*
- *Authors' experiences with methods used in teaching the course*

Jason Keith *is an associate professor of chemical engineering at Michigan Technological University. He received his B.S.Ch.E. from the University of Akron in 1995, and his Ph.D. from the University of Notre Dame in 2001. His current research interests include reactor stability, alternative energy, and engineering education. He was named the 2008 recipient of the Raymond W. Fahien Award for Outstanding Teaching Effectiveness and Educational Scholarship, and in 2010 he was inducted into the Michigan Technological University Academy of Teaching Excellence and was also awarded with the Fredrick D. Williams Instructional Innovation Award at Michigan Technological University.*

David L. Silverstein *is currently the PJC Engineering Professor and an associate professor of chemical and materials engineering at the University of Kentucky, College of Engineering Extended Campus Programs in Paducah. He received his B.S.Ch.E. from the University of Alabama and his M.S. and Ph.D. in chemical engineering from Vanderbilt University in Nashville, Tenn.; and has been a registered P.E. since 2002. Silverstein is the 2004 recipient of the William H. Corcoran Award for the most outstanding paper published in* Chemical Engineering Education *during 2003, and the 2007 recipient of the Raymond W. Fahien Award for Outstanding Teaching Effectiveness and Educational Scholarship.*

Don Visco *is a professor of chemical engineering at Tennessee Technological University, where he has been employed since 1999. Prior to that, he graduated with his Ph.D. from the University at Buffalo, SUNY. His current research interests include experimental and computational thermodynamics as well as bioinformatics/drug design. He is the 2006 recipient of the Raymond W. Fahien Award for Outstanding Teaching Effectiveness and Educational Scholarship as well as the 2009 recipient of the National Outstanding Teaching Award from ASEE.*

Lisa G. Bullard *is a teaching associate professor and director of Undergraduate Studies in the Department of Chemical and Biomolecular Engineering at North Carolina State University. She received her B.S. in chemical engineering from NC State and her Ph.D. in chemical engineering from Carnegie Mellon University. She served in engineering and management positions within Eastman Chemical Co. from 1991-2000. A faculty member at NCSU since 2000, she was named the 2010 recipient of the Raymond W. Fahien Award for Outstanding Teaching Effectiveness and Educational Scholarship.*

SOLUTION THERMODYNAMICS

This course, also commonly called Thermodynamics 2, focuses on mixtures and mixture phase equilibrium as well as reaction equilibrium. Unlike the first thermodynamics course, this course normally consists of exclusively chemical engineering students. Note that since this is typically the second part of a two-part Thermodynamics sequence, some of the advice/ideas/information given for the first Thermodynamics course in our previous work[3-6] are applicable to the Solution Thermodynamics course.

Best Practices / New Ideas

There are certain phenomena within this course that, although working against intuition, can be visualized through experimentation (both desktop and simulation). For example, consider the following straightforward demonstrations that can be performed to show mixture effects:

- *Heat of solution – Mix salt into water and, using a thermocouple placed in the solution, have the students attempt to estimate the heat of solution.*
- *Excess volume – Take a long, thin container and mix 500 ml of ethanol with 500 ml of water. The resulting solution is ~970 ml, which demonstrates that liquid volumes are not additive.*
- *Miscibility – One can show how the ethanol + water and the ethanol + toluene mixtures are miscible, yet the toluene + water mixture forms a miscibility gap.[8]*

Additionally, since changes in molecular-level interactions can manifest themselves in complicated phase behavior, simulation can be utilized to demonstrate these effects in a powerful way. One source for this information is the website for the Etomica environment created by Kofke, which houses many applets, some of which focus on fundamental behavior germane to an undergraduate solution thermodynamics course.[9]

Other recent ideas used to best teach the concepts of this course include:

- *Show students exceptions to the well-known Le Chatelier's Principle.[10]*
- *Promote a graphical view of thermodynamics that emphasizes uncommon intuition[11] and focuses on the benefits of visualization using modern software, such as Mathcad.[12]*
- *Falconer emphasizes the use of concept tests that use classroom response systems to allow immediate feedback from students for formal or informal assessment.[13]*
- *Initiate a discussion on the complications of calculating liquid-liquid phase equilibrium and the potential for false solutions; for example, when the initial guess for the iterative method is too far from the actual solution, it is possible to converge to a local and not a global minimum.[14]*
- *An MS Excel add-in (XSEOS) calculates a variety of thermodynamic properties using both equations of state and Gibbs excess energy models.[15]*
- *There are various applications of a cubic equation of state in calculating mixture phase diagrams and chemical equilibrium using MATLAB (with programs provided).[16]*
- *A recent work describes a combination of experimental and modeling approaches to introduce gas-liquid solubility.[17]*
- *Elliott provides an interesting discussion relating solution non-ideality, including hydrogen bonding, to solubility and volatility in both a qualitative and quantitative manner.[18]*

It is also noted that thermodynamics is a subject area not just encountered in chemical engineering, but in mechanical engineering, chemistry, physics, and other disciplines. Accordingly, educational ideas from those disciplines exist related to thermodynamics, and the interested reader might well want to consider insights and ideas from faculty outside of chemical engineering. For example, the *Journal of Chemical Education* (published by the American Chemical Society) contains many educational articles related to thermodynamics, such as recent contributions on an experimental technique for obtaining Henry's Law coefficients[19] and a laboratory procedure for gas clathrate hydrates.[20] *The Physics Teacher* discusses various fundamental thermodynamics concepts as well as some interesting analyses, such as the thermodynamics of a thermos.[21] Articles on the design of a bench-top, portable refrigeration apparatus for use in a classroom setting can be found in the *International Journal of Mechanical Engineering Education*.[22] Also, *Computer Applications in Engineering Education* publishes articles related to thermodynamics education, such as a recent contribution on the creation of residue curve maps for multi-component mixtures using MATLAB and Mathematica.[23]

Finally, one can utilize this class (or the previous Thermodynamics class) to provide an opportunity for students to design, estimate costs, build, and implement a project related to course concepts. In such an exercise, students are expected to keep track of their budget, set milestones, take notes to record their successes and failures, and prepare a detailed report. Industrial visitors may be interested in attending and reviewing the presentations. To promote efficiency and reuse, projects in the following year can be used to improve upon the existing design. Some example projects have demonstrated ethanol distillation through building a still and the appearance of miscibility gaps at different temperatures for the water + propylene glycol n-propyl ether system.[24]

Trouble Spots

Trouble spots for this course include:

- *Often students become bogged down in the calculations and lose the big picture. Phase equilibrium calculations for mixtures (especially with equations of state) are complicated, and there is a tendency to work towards arriving at an answer with little appreciation or interpretation of the result. Depending on the situation, the use of an Excel add-in such as XSEOS[15] or a web applet to determine phase equilibrium from an equation of state may be more appropriate.[25, 26]*
- *Reading mixture phase diagrams can be confusing to*

students. By utilizing the Journal of Chemical and Engineering Data*, students can find a wide variety of phase diagrams that can be used to spark discussions on the Gibbs Phase Rule, Raoult's Law, miscibility gaps, etc.*

- *Nomenclature and symbols can be problematic, especially if there are discrepancies between the Thermodynamics course and the students' previous chemistry or physics course. In this course (and between different books), symbols have subscripts, hats, carats, superscripts, overbars, etc. A poster or handout that describes each modification to a symbol, posted in the classroom (or prepared for the student), could be of great benefit.*

Author Experiences

At Tennessee Technological University, the Solution Thermodynamics course and the Separations course have been merged into a single course with an integrated laboratory experience. This approach has the benefit of using the theories and models prevalent in solution thermodynamics more transparently applied in a separations process, be it binary distillation, crystallization, or liquid-liquid extraction. Additionally, the author readily incorporates the following in the Solution Thermodynamics course:

- *Open-ended, relevant design problems such as making ethanol starting from a bio-mass source (such as switchgrass)*
- *Incorporation of a critical-thinking framework[27] to examine claims related to course concepts/materials*
- *Homework problems tagged with Bloom's Taxonomy levels so that the instructor is reminded to strive towards problems and solutions that focus on analysis/synthesis/evaluation skills*
- *A square-well mixture Java applet[9] that allows the user to change the cross-interaction parameter and cause a very visual phase splitting; used in conjunction with a desktop demonstration of liquid-liquid phase splitting, provides a powerful micro- and macro-level examination of this phenomenon*
- *Generating Pxy or Txy diagrams using Raoult's Law for systems that need non-ideal approaches to motivate the use of such techniques; revisiting those same systems and incorporating both activity and fugacity coefficients, plotted with the experimental data, serves as a good reminder and contrast for the need for non-ideal approaches*

HEAT AND MASS TRANSFER

The field of heat and mass transfer was revitalized as a fundamental field of study in 1960 through the publication of the text *Transport Phenomena*.[28] Currently, heat and mass transfer remains a popular subject in the research literature.

Best Practices / New Ideas

Recent advances in simulation and modeling allow for a marked change in how heat and mass transfer can be taught in the classroom. There are several examples published in the literature using computational fluid dynamics,[29-31] numerical solutions,[32, 33] similarity solutions,[34] molecular simulations,[9,35, 36] and desktop modules.[37]

- *Sinclair[29] describes the use of Fluent software in the undergraduate curriculum. Although focused on fluid dynamics, the teaching principles illustrated in this paper can be extrapolated to heat and mass transfer courses.*
- *Thompson[30] utilizes the PDE toolbox feature in Matlab to solve a variety of problems in fluid mechanics, heat transfer, and solid mechanics.*
- *Keith, et al.,[31] employ COMSOL Multiphysics to illustrate how a variety of problems in fluid mechanics, heat and mass transfer, and reaction kinetics can be extended to fuel cell applications.*
- *Goldstein[32] solves free convection problems using similarity variables and a numerical simulation of an initial value problem.*
- *Binous[33] uses Mathematica to solve membrane permeation problems using the complete mixing model (algebraic solution) and the cross-flow, counter-current, and co-current systems (numerical solution).*
- *Subramanian[34] applies similarity methods to three classical problems: diffusion in a semi-infinite domain, flow past a flat plate, and the Graetz problem for flow into a rectangular channel with isothermal walls.*
- *Keffer, et al.,[35] illustrate the use of molecular-level simulations to predict gas diffusivities.*
- *Minerick[37] demonstrates ways to use desktop-sized modules to reinforce fundamental heat transfer concepts, including 1-dimensional heat conduction, the effect of contact resistance, steady-state and transient heat generation, and convection.*

There are many good websites with simulations appropriate for undergraduate students in heat and mass transfer courses. The following is a partial listing of those highlighted recently in the literature or at conferences:

- *As mentioned previously, the Etomica environment[9, 36] provides relevant Java-based molecular simulations on its website.*
- *Coker, et al.,[38, 39] describe simulation of gas separation using polymer membranes.*
- *Zheng and Keith[40-42] describe the use of Java applets to help students visualize heat and mass transfer.*

Two papers by Flynn, et al.,[43, 44] focus on integrating green engineering principles into a heat transfer course. The first paper[43] describes several traditional heat transfer problems that are uniquely coupled with green engineering principles.[45, 46] Example problems include: conduction shape factors and rainforest conservation, natural convection and energy-efficient lighting, natural convection through windows, life-cycle studies, and radiation heat transfer for comfort and energy efficiency. The second paper[44] describes assessment of the teaching tools.

Some novel experiments in heat and mass transfer include:

- *Investigation of transport of environmental pollutants in groundwater using dissolved pollutants and colloids[47]*
- *Experiments and modeling of lozenge dissolution to simulate drug delivery processes in the human body[48]*

- *Rate of drying curves and unsteady-state heat transfer in cooking of French fries*[49]
- *Designing, building, and testing of small compact heat exchangers*[50]
- *Carbon dioxide loss from a carbonated beverage container*[51]
- *Experiments and modeling of the hemodialysis of creatinine to enhance bioengineering experiences in the chemical engineering curriculum*[52]

Trouble Spots

Trouble spots for this course include:

- *Students may possess weak math skills. Instructors can develop handouts to step students through difficult solution processes (such as solving differential equations). Reference 53 contains an example. Instructors could also have students practice using in-class problems and homework assignments before testing them.*
- *Students may have difficulty in connecting highly theoretical content to real industrial applications—if there is an internet-connected computer and projector in the classroom, instructors can use online and/or laboratory demonstrations to make a strong connection. This connection can also help students with their follow-on classes.*
- *Students often do not know order-of-magnitude values for heat exchanger area, mass transfer coefficients, dimensionless groups, etc. The instructor can provide them with general values on a handout they can paste in the front of their textbook. For an example, see Reference 54 or the books by Woods*[55] *or Fogler.*[56]
- *Students struggle with knowing when to eliminate terms in the governing equations. If they are provided with the aforementioned handouts, they will be prepared for more advanced homework and exam questions.*

Author Experiences

At Michigan Technological University, efforts have been made to bring computer technology and hands-on problems into the Transport / Unit Operations 2 course. As such, the students have been introduced to simulations and modeling in various forms.

- *A homework problem has students design an oven for cooking turkeys following the Java applet of Zheng and Keith.*[40-42, 57]
- *Via homework assignments and a project, students are asked to create their own steady-state and unsteady-state finite difference models for mass diffusion in MATLAB.*
- *Students have a homework problem comparing the exact solution for a steady- or unsteady-state diffusion problem with that from COMSOL Multiphysics.*[31] *The students then have to solve a harder problem with the software (for which no analytical solution is available).*
- *Students are introduced to molecular modeling and how it is used to calculate transport properties.*[9, 35, 36]
- *Students are given experimental data from a laboratory course and are asked to use it to predict transport properties.*
- *Students are given daily handouts—the handouts are either meant to aid them in solving problems in transport phenomena (for example see Reference 53) or a daily in-class problem (following the principles of problem-based learning) where the students apply the lecture material they just learned.*

KINETICS AND REACTOR DESIGN

Kinetics, catalysis, and reactor design distinguish chemical engineers from other engineers and remain active research fields.

Best Practices / New Ideas

Like other subject areas, simulation and modeling are used in kinetics and reactor design. There are several examples published in the recent educational literature[58-64] that will now be summarized.

- *Stochastic simulations of chemical reactions*[58, 59]*: Martinez-Urreaga, et al.,*[58] *use MATLAB to simulate the reversible reaction A ↔ B, while Fan, et al.,*[59] *simulate the thermal death kinetics of a cell population.*
- *Computational fluid dynamics*[60-62]*: Lawrence, et al.,*[60] *use CFX commercial software to incorporate non-ideal reactors into the curriculum. They develop residence time distributions in tubular reactors and use them to determine conversion for a reaction using Langmuir-Hinshelwood kinetics. Madiera, et al.,*[61] *simulate a complex two-dimensional reservoir, determine the residence time distribution and predict the conversion during steady-state operation. Bakker, et al.,*[62] *illustrate non-ideal effects in various reactor types with color images of CFD simulations.*
- *Parulekar*[63] *uses Mathcad to perform numerical simulations of several fundamental kinetics and reactor design problems, including estimation of kinetic parameters, autocatalytic reaction and space times for operation of continuous and plug-flow reactors, gas phase sulfur dioxide reaction to sulfur trioxide, predicting equilibrium composition of a reaction mixture, steady-state multiplicity in continuous reactors, membrane reactors, series-parallel reactions, and consecutive reactions.*
- *It is noted that reactions can also be simulated in process modeling software such as ChemCAD, Aspen, Hysis, and UniSim for various reactor types.*
- *Wilcox*[64] *describes the utility of computational quantum chemistry for solving advanced problems such as the development of rate expressions from transition state theory.*

A paper by Muske and Myers[65] integrates principles of statistics and experimental design into a project to determine the forward and reverse reaction kinetic rate constants for ethylene hydrolysis into ethanol. Complicating the problem is that students need to determine the Arrhenius parameters for these reactions. Students are given a budget and request "experimental" runs from which they are supplied data by e-mail one day after their request. A process simulation with statistical fluctuations is used to generate results and mimic a real experimental study. They must decide when they have enough data (or when they run out of money), and possibly adjust their experimental plan in order to perform the analysis.

The Safety and Chemical Engineering Education (SACHE) program is a joint effort between the American Institute of Chemical Engineers Center for Chemical Process Safety and academic institutions. Founded in 1992, the committee typically organizes a yearly workshop to educate chemical engineering faculty on the importance of safety education. Their website[66] features problem sets and web modules that can be used in the classroom. It is noted that some features of the site require a password for access. An example module is the Chemical Reactivity Hazards Instructional Module[67] developed by Robert Johnson of Unwin Co. The module can be used to motivate the importance of safety in kinetics and reaction engineering. It highlights several major incidents where uncontrolled chemical reactions can result in devastating consequences. Additional safety material is available in Crowl and Louvar's textbook.[68]

Other resources that could be used in a kinetics course include:

- *Dartmouth University has an online JAVA periodic table[69] that contains puzzles, quizzes, and a molar mass calculator. The same group has a JAVA kinetics plotter[70] that can be used to fit zero-, first-, or second-order kinetics to supplied experimental data.*
- *The University of California at Irvine has a JAVA applet to simulate molecular motion, collision, and reaction.[71] The user enters initial concentration of red, yellow, green, and blue molecules. Upon the interaction of a red and yellow molecule, green and blue molecules are formed. The reaction is reversible, and the user can enter the forward and reverse reaction rate constants.*

Laboratory experiments in kinetics and reactor design include:

- *Hesketh, et al.,[72] describe an experiment to explore the heterogeneous reaction of propane in an automobile catalytic converter. The students measure the compounds exiting the converter using Fourier transform infrared spectroscopy. Furthermore, a simple model is used to fit the experimental data to determine reaction rate parameters.*
- *Shonnard, et al.,[73] present a batch fermentation experiment to produce l-lysine in the senior laboratory. The students in the lab each perform an experiment that is part of a larger factorial design matrix. The students then share data and analyze all of the results.*
- *Li, et al.,[74] formulate an experiment to study the growth of yeast in a small-scale bioreactor. Students measure the concentration of yeast cells and glucose, and after learning about biological reaction kinetics, they estimate the doubling time for the yeast.*
- *Dahm, et al.,[75] outline a set of micromixing experiments to use in the undergraduate reaction engineering course. In a lecture on micromixing, the students are taught about the perfectly mixed and totally segregated reactor models. Experiments are performed on a system with parallel competitive reactions in a 2 L reactor with baffles and a mixer, and also in a 600 mL beaker with a magnetic stir bar. Results show that the selectivity is higher in the baffled reactor.*
- *Rice, et al.,[76] describe an experiment for propane hydrogenolysis on an alumina-supported platinum catalyst. Students run the reactor to obtain power law kinetic parameters (to determine reaction order in propane and hydrogen) as well as Arrhenius parameters.*

Trouble Spots

Trouble spots for this course include:

- *Although kinetics and reaction engineering courses are typically not as math-intensive as, say, transport phenomena, weak math skills may prevent students from carrying out solutions to determine concentration as a function of time for complex kinetics, analysis of axial dispersion in reactors, etc. Repetition through homework assignments can reinforce these concepts and build student confidence prior to exams.*
- *Students may have difficulty recalling material from previous courses that may be considered prerequisites for the kinetics and reaction engineering course. Recalling fundamental chemistry, especially organic chemistry, can be difficult for even advanced students. The instructor can summarize some of the important reactions to aid students in feeling comfortable in an upper-level course.*
- *Students often do not know order-of-magnitude values for reactor volumes or pressure drops. The instructor can provide them with general values on a handout they can paste in the front of their textbook. For an example see Reference 54 or the books by Woods[55] or Fogler.[56]*
- *Students do not know many of the assumptions in the basic reactor models (batch, continuous stirred tank reactor, plug flow reactor) and how valid they are in laboratory or industrial applications. The instructor can demonstrate or assign problems utilizing CFD[60-62] to illustrate batch / CSTR reactors with dead zones, bypassing, poor mixing, and strong concentration gradients or illustrate plug flow reactors with axial dispersion, poor packing, etc.*

Author Experiences

At Michigan Technological University, efforts have been made to bring computer technology and hands-on problems into the Kinetics and Reactor Design course.

- *Students are asked to use COMSOL Multiphysics to solve problems involving diffusion and reaction in catalyst pellets.[31]*
- *Students are asked to write their own computer programs to simulate temporal evolutions in species concentration and temperature profiles.[63]*
- *An extra emphasis is placed on chemical reactivity and reactor safety.[62]*
- *Students are given experimental data from a laboratory course and are asked to use it to predict reaction rates and rate constants.*
- *The assumptions behind different reactor models are continuously emphasized. Efforts are also made to introduce non-ideal reactor models, and the advantages and disadvantages of using these models are also stressed.[75]*

PROCESS CONTROL

This course tends to stand alone in the chemical engineering curriculum, seeming to students (and some instructors) somehow disconnected from other upper-level chemical engineering courses. Coverage normally includes mathematical modeling and dynamic simulation, Laplace transforms and transfer functions, linear dynamic responses for various inputs, controllers, instrumentation and valves, closed-loop analysis, stability analysis, controller tuning, frequency response, and advanced control strategies.

Best Practices / New Ideas

Of all the courses in the chemical engineering curriculum, this one may have the most variability in how it is taught. Prior to discussing teaching methods, various approaches to course content will be discussed.

A recent article published by the International Society of Automation magazine *InTech* reported on the views of prominent chemical engineers regarding the role of process control instruction.[77]

- *Douglas Cooper (University of Connecticut, Control Station,[78] and ControlGuru.com[79]) suggests that the course provide a "practical skill set... including enough theory to excite those destined for graduate study."*
- *Cecil Smith (formerly of LSU and currently a consultant) states, "We teach fundamental principles, but include only theory relevant to engineering practice," and "Focus on basic regulatory control, and do it well. Leave optimization, model predictive control, etc., to subsequent courses and advanced-degree programs."*
- *Jim Riggs (Texas Tech and author of* Chemical and Bio-Process Control*[80]) states, "This is the classic question of theory vs. practice in engineering education. The key to this problem is to provide control courses that provide basic industrially relevant skills while also providing a fundamental understanding of process control and process dynamics."*

Riggs also states[77] that the course should teach students to:

- *Understand the unique characteristics of proportional, integral, and derivative control action; the concept of stability; and the difference between linear and nonlinear systems.*
- *Troubleshoot control loops, tune control loops, and make basic control design decisions.*

There is continuing debate over whether or not to use the Laplace domain, or to remain in the time domain. Furthermore, the utility of frequency response methods often results in similar debates among members of academia and industry.

Tom Edgar (University of Texas at Austin and co-author of the textbook *Process Dynamics and Control*) suggests[81]:

- *De-emphasize frequency response, but keep Laplace transforms.*
- *Reduce coverage of multiple approaches for PID controller tuning.*
- *Increase use of simulation in sophomore and junior courses.*
- *Introduce a number of short laboratory experiences.*
- *Use case studies to show how process control can solve real engineering problems.*
- *Teach process control in the senior year.*

A thorough discussion by authors of several process control textbooks about what to teach in process control was recently published.[82]

Once the decision of what to teach has been made by your program, preferably in conjunction with feedback from the employers of your graduates, the task of choosing how to teach the course begins. There seems to be general agreement that a combination of experiment and simulation will help students move from theory to application. In some cases, it may make more sense to move from application to general theory. If this inductive approach is taken, some suggestions can be found in the literature:

- *Moor and Piergiovanni[83] describe the use of small modular kits and Control Station.*
- *Silverstein[84] uses unit operations laboratory-scale apparatus and MATLAB/Simulink.*
- *Henry[85] demonstrates simulation and remote experiments on batch distillation.*

Additional laboratory ideas include:

- *Young, et al.,[86] describe a nonlinear, MIMO salt-mixing process control laboratory experiment.*
- *Rusli, et al.,[87] demonstrate the use of multivariable control for a quadruple-tank process control experiment.*
- *Long, et al.,[88] suggest experiments on air-pressure tank systems.*
- *Muske[89] uses a simple tank in a process control laboratory.*

Web resources include:

- *McMaster University[90, 91] hosts a web page including numerous resources for teaching controls.*
- *Henry[92] has a number of remote laboratories available online.*

Software resources include:

- *Loop-Pro Trainer (formerly known as Control Station)[93]*
- *MATLAB with Simulink,[94] a modeling interface that uses the same block notation used in most texts*
- *A numerical approach with Microsoft Excel®[95]*
- *Excel/VBA based simulation[96]*

Trouble Spots

Trouble spots for this course can include:

- *Application of dynamic mass and energy balances. This may not have been covered much in prior courses, so a detailed review of a relevant problem like a step response for heated tanks in series may be appropriate.*
- *Not understanding the physical meaning of the Laplace variable "s". Despite faculty efforts, this concept will likely remain a mystery to most students. Instead, focus on how conservation laws in the Laplace domain can be arranged to yield key information about process behaviors through parameters such as gains and time constants.*

- *Introducing computing tools too early or too late. Students must understand the how and why before actively developing models with software like Simulink.[94] The appropriate time to introduce them will depend on your curriculum, but probably should be after students have mastered modeling fundamentals and can at least handle simple Laplace domain solutions for open- and closed-loop systems by hand. Some simulation tools, like Loop-Pro,[93] can be used for inductive instruction on principles of control without requiring significant mathematical analysis.*
- *Losing sight of practical control. Better control can always be obtained—at a cost. Students must continually be reminded that there is always an optimal level of control, dependent on the cost to implement control vs. marginal profit from enhanced control. The roles of safety, security, and environmental protection should also be considered.*

Author Experiences

At the University of Kentucky, the emphasis of recent changes in the course has been to bring inductive laboratory and simulation experiences into the course.[84] The first meeting of the course brings students down to the lab to observe principles of process control where they act as the controller. They turn knobs and flip switches to control flow, pressure, and level, and gain experience that serves as a foundation for discussions of principles of process control. Other approaches adopted include:

- *Use of Simulink after students have completed a module on modeling and Laplace transformation. Using simulators from the start of the course had discouraged students from developing an understanding of what the simulators were doing, treating them as a "black box."*
- *Use of other simulators (VBA,[96] Loop-Pro[93]) to allow students to explore control concepts. The simulators are far less time-consuming and more flexible than laboratory counterparts.*
- *Emphasis on practical control following the modeling module, with particular focus on the economic constraints on control. Students are frequently asked to consider what investment in hardware and what recurring maintenance costs would be required to implement a control scheme, and then consider whether the marginal improvement results in sufficient marginal profit to justify the project.*
- *Assigning a role in an industrial project to reduce energy costs in a process at a local specialty chemical plant. Students work across multiple courses (including teams with underclassmen) to solve a real industrial problem.[97]*
- *Requiring students to work with technology students at another institution to perform a detailed design of a control system.[98]*

SENIOR DESIGN

The senior or "capstone" design course can be intimidating to some faculty. In many departments the course was traditionally taught by a retired industrial practitioner who had a good idea of the types of deliverables that were representative of what students would encounter in the workplace, but this may not be the case today. In addition, the advent of process simulators in the 1970s and 1980s has had a huge impact on the way that senior design is taught. The senior design course typically includes both traditional lecture content as well as a capstone project. Academic content typically includes flowsheet synthesis and development, process simulation, process economics, and equipment design/heuristics. Depending on the background of the instructor and whether the course is one or two semesters, a laundry list of additional topics might include sustainability and "green design" concepts,[99] process safety,[100] Good Manufacturing Practice, Six Sigma,[101] optimization,[102] selecting materials of construction, reading P&ID's, heat exchanger network or reactor network synthesis, environmental regulations, engineering ethics, batch scheduling, and product design.[103] Senior design is also the last opportunity to reinforce "soft skills" such as teamwork[104, 105] and communication.[106, 107] Furthermore, the AIChE Centennial Conference has a session on design featuring many of the design textbook authors. Videos of these talks are available online.[7]

Best Practices/New Ideas

Whether the course is one semester or two will significantly impact how the course is organized, the content that can be covered, and the scope of the design project. According to a recent survey conducted by John Wiley based on a response from 50 departments, U.S. chemical engineering departments are split down the middle—half teach one design course, and half teach a two-semester design sequence.[108]

Instructors have several challenges related to the structure and organization of the course:

- *Departments that teach one design course must be very selective and choose which content is most important for their graduates. Design projects for a one-semester offering might be best structured as multiple smaller problems that reinforce the course content being covered. Departments that teach two design courses have more flexibility to cover additional specialized content, present information on product design as well as process design, invite guest speakers, and pose design projects that stretch over an entire year.*
- *Coming up with new projects each year can be a challenge for instructors. Starting early is important since it may take some time to define prospective projects and mentors. In addition to gleaning ideas from the literature (discussed below), solicit departmental faculty at the end of the spring semester or in the summer to generate some ideas. Contact enrolled students early in the summer and invite them to define their own project subject to some constraints on what the project should include. If your campus has an Engineering Entrepreneurship class,[109, 110] partner with them to include your students.*
- *Industrial partners, especially if the department is located near industry or research organizations, can serve as sources of design projects and mentors. The local AIChE section could be a good resource for local practitioners who would be willing to participate. Industrial alumni*

who have been through the course can be excellent mentors because they are familiar with the deliverables required. In addition, industrial advisory boards may be helpful in identifying key skills expected for new employees, which may help define course content.

- *Additional project advisors may be needed depending on the class size and the instructor's background. Some departments enlist all faculty to propose and sponsor one design project each year. Other sources of mentors include faculty in other related departments (*e.g.*, Materials Science, Food Science, Environmental Engineering, or Computer Science); this is especially effective if the students are double majors in that department.*
- *If students are working on projects that require experimental work or small-scale construction, funding can be an issue. Most departments have funds available for laboratory equipment and supplies, but funding levels for design must be considered when proposing and defining the scope of projects. Some departments ask companies to sponsor projects for a flat fee (*e.g.*, $5,000) or the cost of materials. Industrial advisory board members/companies or alumni may be additional sources for senior design funds.*
- *Depending on the deliverables, the learning outcomes, and the number of mentors involved, assessment can be a challenge. Approaches to this issue are discussed by Baker, et al.,[111] Rogge, et al.,[112] and Davis, et al.[113]*
- *Addition of new material may be necessary. One example is solids processing, which is common in chemical engineering practice, but is not usually covered extensively in the curriculum. Good references are available from Davey and Garside,[114] Rhodes,[115] Wibowo and Ng,[116] and Hill and Ng.[117]*

Examples of design projects:

- *The text by Turton, et al.,[118] contains six complete senior design projects in addition to the extensive list of projects on their website.[119] Shaeiwitz and Turton[120] describe two examples of novel capstone design projects: an ice cream manufacturing process and the design of a transdermal drug delivery patch. In addition, they have developed additional product design projects.[121]*
- *The text by Peters, et al.,[122] includes problem descriptions for five major projects, five minor design problems, and seven practice-session problems.*
- *Weiss and Castaldi[123] describe a tire gasification senior design project that integrates laboratory experiments and computer simulation.*
- *Benyahia[124] outlines a project involving vinyl chloride monomer (VCM), emphasizing its compliance with ABET 2000 criteria.*
- *Hernandez, et al.,[125] present a biodiesel design project that highlights the potential contributions of chemical engineering to areas such as new energy sources, global warming, and environmental sustainability.*

AIChE National Student Design Competition problems are also available each year in the fall to department chairs and student chapter advisors. They may be completed by students over the course of 30 days any time during the year (if they choose to enter their report into the competition). An archive of past problems and solutions is available from AIChE.

Examples of additional ideas for course content and structure:

- *Organizations such as AIChE,[126] the World Congress of Chemical Engineering,[127] and NASA[128] sponsor annual design competitions. Kundu and Fowler[129] discuss the use of engineering design competitions to engage students. Often these involve the use of multidisciplinary teams, which is discussed by Redekopp.[130]*
- *Silverstein[131] and Hadley[132] describe the use of wikis in senior design as a project-management tool.*

Web resources:

- *Cadwell, et al.,[133] feature a series of short online videos on "Topics in Engineering Design" that include communication in design, design considerations, the design process, and patents and literature.*
- *The On-Line Ethics Center at the National Academy of Engineering,[134] the Markkula Center for Applied Ethics,[135] and the Center for the Study of Ethics in Society[136] have websites with case studies and other materials for teaching engineering ethics.*
- *As described earlier, process safety modules are available through the Safety and Chemical Engineering Education (SACHE) program.[66]*
- *The EPA makes available exposure assessment tools and models.[137]*
- *Miller[138] has posted a set of slides on cost estimation.*
- *Milligan[139] hosts a website with specific process equipment costs estimates.*
- *UT Austin[140] lists helpful reference books, periodicals, and trade journals as resources for chemical pricing.*

Software resources:

- *Process simulators typically used in senior design include Aspen Dynamics, Aspen HYSYS, Aspen Plus, Aspen Batch Process Developer (formerly Batch Plus), CHEMCAD, PRO/II, SuperPro Designer, and UNISIM.*
- *The Aspen academic suite has several new modules. Aspen Process Economic Analyzer (formerly Icarus Process Evaluator) can be used for interactive equipment sizing as well as estimation of purchase costs and total investment. The package now includes modules for adsorption and batch distillation.[141]*
- *The text and website by Seider, et al.,[108] include self-study examples and multimedia instruction, focusing on Aspen Plus and HYSYS.*

Trouble Spots

Trouble spots for this course can include:

- *Team Dynamics: Although most students have worked in groups during unit operations lab or in homework groups, senior design is by far the biggest group project that many of them have tackled. Instructors should require design teams to define team expectations, roles, and responsibilities early in the semester. Providing instruction or resources on the phases of team performance, personality types,[142] and learning styles[143] can alleviate potential* *problems. An additional suggestion of Sauer and Arce[144] is that teams get together and, as their first task, develop an "Agreement of Cooperation." This agreement will serve as the bylaws of the team and can only be changed with a majority vote of the team members. Administering a peer evaluation tool is essential since much of the course grade will depend on the group project. Instructors might also consider a mechanism that reflects individual contribution; for example, students could be required to keep a design notebook[145] or submit their individual written contributions. This can be helpful if there is dissent within the team about an individual's contribution.*

- *Writing and Speaking Deliverables: The senior design report is likely the most formal and the longest document that students will produce. Even if students have taken a technical writing course, many are overwhelmed and do not feel confident about structure, format, and citation details. Some campuses have Writing and Speaking Centers on campus or in-house technical writing consultants who can assist by providing resources, giving a class lecture, or even reviewing student work. Allowing groups to submit a draft to the instructor a week in advance for a review can identify major problems while still allowing time for correction.*
- *Originality of student writing: Design instructors may want to use software such as turnitin.com[146] (or suggest it to students) to avoid plagiarism issues.*
- *Student procrastination: The combination of "senioritis" and procrastination can result in students trying to cram in months of works into weeks or days. Instructors can help students pace themselves by structuring the project into deliverables that are spread over the one or two semesters. For example, in a two-semester sequence in which the projects are assigned in October, students could produce a literature review/technical background in November, a status report in February, an oral presentation in March, and the final report and poster in April. Design teams should submit a project schedule and work plan early on as one of the deliverables. Some instructors require students to produce progress reports in memo form periodically during the duration of the project. Finally, depending on the size of the class, the instructor could meet with each team or each project manager regularly throughout the semester to hold them accountable.*

Author Experiences

At North Carolina State University senior design is taught as a two-semester sequence. The first semester is a more traditional lecture-style class with instructional design content, with students being assigned to teams early in the fall semester and beginning work on their design project, which carries into the spring semester. The spring is focused primarily on the project, with classroom time being devoted to guest lectures that address topics relevant to professional development. Additionally, the author has incorporated the following in the Senior Design course:

- *Guest speakers, in particular successful alumni, address professional development topics, career paths, and non-traditional careers such as medicine, law, pharmacy, business, teaching, or entrepreneurship. Financial planning, business and electronic etiquette, and professional dress are issues that students will soon face. Alumni panels on "Making the Transition from Student to Employee," "Changing Jobs," and "Graduate School" can be a very effective way to address these issues.*
- *The traditional oral presentation can be moved to midsemester as a status update; this enables advisors to provide feedback that can be incorporated prior to the final report. The author holds an end-of-semester poster session and invites students' parents, the Industrial Advisory Board members, and current junior students. Starting off with a 2-minute summary of each project and then adjourning to a 60- or 90-minute poster session can be an effective way of having students present their work and creates a celebratory environment instead of the high stakes formal presentation. Parent response to this type of event is typically very positive; it may be the first time they have been invited to participate in an event at the university involving their student. This also gives rising seniors an opportunity to see what is required for a senior capstone project. Giving awards for "best in show" recognizes those students who make exceptional effort and helps rising seniors see where the bar is set.*
- *CATME[147, 148] is an easy-to-use online tool that collects and analyzes self and peer evaluations of team members' contributions. The peer-evaluation instrument is administered with each major deliverable, and team members receive feedback on their individual performance compared to the group average after each submission. Any low-performing students are identified by the instructor, and the team meets with the instructor to discuss the issue so that it can be addressed early. Final peer evaluations are submitted one week before the end of the semester to allow time for rebuttal if necessary.*
- *The author provides instruction or resources in technical writing, oral presentations, and how/when to cite.[149, 150] In addition, students are provided with exemplary documents from a previous year that demonstrate expectations.*
- *The text by Turton, et al.,[118] contains a CD-ROM with the latest version of CAPCOST, a tool for evaluating fixed capital investment, full process economics, and profitability—now expanded with cost data for conveyors, crystallizers, dryers, dust collectors, filters, mixers, reactors, and screens. It also contains the HENSAD tool for constructing temperature-interval, cascade, and temperature-enthalpy diagrams; estimating optimal approach temperatures; and designing heat exchanger networks.*
- *The Thomas Register[151] is a useful database for equipment vendors.*
- *Bullard, et al.,[152] provide three web-based case studies in the area of biomanufacturing for the production of co-protein, citric acid, and ammonia. Supporting materials have been developed for each case study, including a problem statement, an exemplary solution, and a summary of the difficulties and typical errors that might be encountered.*

CONCLUSIONS

This paper has described some of the best practices for use in the following chemical engineering courses that traditionally occur later in the curriculum: solution thermodynamics; heat and mass transfer; kinetics and reactor design; process control; and senior design. A common thread is in the deviation from the traditional lecture format. When this is done, the students are given the opportunity to take ownership of their own learning. Popular methods include the use of in-class demonstrations, hands-on activities, tours of the unit operations lab, and seeing a movie or simulation of a concept. Additionally, the softer skills of engineering are finding their way into the classroom, with the most popular ones being an increased emphasis on communication and teamwork skills.

It has been our collective experience that incorporating novel methods into the classroom can increase learning as students in the latter part of the curriculum transition from the classroom to the workplace or graduate school. Interestingly enough, the addition of many of these novel methods does not require a significant amount of effort, yet there may be considerable benefit for the students involved.

It can be overwhelming to consider substantial changes to an established course, but an approach that has worked for the authors is to start with a course that we have taught before. We first identify a handful of new ideas to bring into the classroom for the next time we teach the course. As we implement them, we will ask for informal feedback from students. This will often be reinforced through the formal course evaluations. Then, the next time the course is taught, we make modifications as we see fit. After a few years, the course may look totally different from the original course offering.

For copies of the presentation slides from the Summer School, contact one of the authors.

REFERENCES

1. Silverstein, D. L., D.P. Visco, and J.M. Keith, "New Ideas for Old Courses: Upper Division," presented at 2007 ASEE-AIChE Summer School, Pullman, WA
2. Keith, J.M, D.L. Silverstein, and D.P. Visco, "Ideas to Consider for New Chemical Engineering Educators: Part 2 (Courses Offered Later in the Curriculum)," *Proceedings* of the 2009 ASEE Annual Conference & Exposition, ASEE (2009)
3. Silverstein, D.L., D.P. Visco, and J.M. Keith, "New Ideas for Old Courses: Lower Division," presented at 2007 ASEE-AIChE Summer School, Pullman, WA
4. Keith, J.M, D.L. Silverstein, and D.P. Visco, "Ideas to Consider for Chemical Engineering Educators Teaching a New 'Old' Course: Freshman and Sophomore Level Courses," *Proceedings* of the 2008 ASEE Annual Conference & Exposition, ASEE (2008)
5. Keith, J.M, D.L. Silverstein, and D.P. Visco, "Ideas to Consider for Chemical Engineering Educators Teaching a New 'Old' Course: Freshman and Sophomore Level Courses," *Proceedings* of the 2008 AIChE Annual Meeting, (2008)
6. Keith, J.M, D.L. Silverstein, and D.P. Visco, "Ideas to Consider for Chemical Engineering Educators Teaching a New 'Old' Course: Freshman and Sophomore Level Courses," *Chem. Eng. Ed.*, **43**(3), 209 (2009)
7. Directions to Education Topical Conference video presentation archive available at AIChE Education Division website, <http://www.aiche.org/DivisionsForums/ViewAll/EDU.aspx>, accessed April 2010
8. Toghiani, R.K. "Chemical Engineering Thermodynamics: Transforming 'Thermo' Lectures into a 'Dynamic' Experience," *Proceedings* of the 1998 ASEE Annual Conference & Exposition, ASEE (1998)
9. Kofke, D. etomica Molecular Simulations API, <http://www.etomica.org>, accessed April 2010.
10. Corti, D.S., and E.I. Frances., "Exceptions to the Le Chatelier Principle," *Chem. Eng. Ed.*, **37**(4), 290 (2003)
11. Misovich, M.J. "Making Phase Equilibrium More User-Friendly," *Chem. Eng. Ed.*, **36**(4), 284 (2002)
12. Dickson, J.L, J.A. Hart and W-Y. Chen, "Construction and Visualization of VLE Envelopes in Mathcad," *Chem. Eng. Ed.*, **37**(1), 20 (2003)
13. Falconer, J.L. "Use of ConcepTests and instant Feedback in Thermodynamics," *Chem. Eng. Ed.*, **38**(1), 64 (2004)
14. del Mar Olaya, M., I. Ibarra, J.A. Reyes-Labarta, M.D. Serrano, and A. Marcilla, "Computing Liquid-Liquid Phase Equilibria," *Chem. Eng. Ed.*, **41**(3), 218 (2007)
15. Castier, M., "XSEOS: An Open Software for Chemical Engineering Thermodynamics," *Chem. Eng. Ed.*, **42**(2), 74 (2008)
16. Fonseca, I.M.A., J.P.B. Almeida, and H.C. Fachada, "A Lab Experiment to Introduce Gas/Liquid Solubility," *Chem. Eng. Ed.*, **42**(3), 147 (2008)
17. Nasri, Z., and H. Binous, "Applications of the Peng-Robinson Equation of State Using MATLAB," *Chem. Eng. Ed.*, **43**(2), 115 (2009)
18. Elliott, J.R., "A Simple Explanation of Complexation," *Chem. Eng. Ed.*, **44**(1), 13 (2010)
19. Short, L.C. and T. Benter, "Principles of Solution Thermodynamics: Demonstration of Nonideal Behavior of Henry's Law. An Undergraduate Laboratory Experiment," *J. Chem. Ed.*, **83**, 1233 (2006)
20. Prado, M., A. Pham, R. Ferazzi, K. Edwards, and K. Janda, "Gas Clathrate Hydrates Experiment for High School and Undergraduate Laboratories," *J. Chem. Ed.*, **84**, 1790 (2007)
21. Berger, R., "Some Interesting Thermodynamics of the Thermos Flask," *The Physics Teacher*, **45**, 270 (2007)
22. Abu-Mulaweh, H., "Portable Experimental Apparatus for Demonstrating Thermodynamics Principles," *Int. J. Mech. Eng. Ed.*, **32**, 223 (2005)
23. Binous, H., "Residue Curve Map for Homogenous Reactive Quaternary Mixtures," *Computer Applications in Eng. Ed.*, **15**, 73 (2007)
24. Visco, D.P, "Incorporating Projects and Problems in a Thermodynamics Course to Improve Critical Thinking/Real World Problem Solving," Presented at the American Society for Engineering Education Annual Meeting, 2008
25. Barrie, P.J., "JavaScript Programs to Calculate Thermodynamic Properties Using Cubic Equations of State," *J. Chem. Ed.*, **82**, 958 (2005)
26. Barrie, P.J., JavaScript Programs for Solving Cubic Equations of State <http://www.cheng.cam.ac.uk/~pjb10/thermo/index.html>, Accessed April 2010
27. Schick, T., and L. Vaughn, *How to Think About Weird Things: Critical Thinking For a New Age*, 3rd Ed. (2001)
28. Bird, R.B., W.E. Stewart, and E.N. Lightfoot, *Transport Phenomena*, Wiley, New York, 1960 (1st Ed.)
29. Sinclair, J.L., "CFD Studies in Fluid-Particle Flow," *Chem. Eng. Ed.*, **32**(2) 108 (1998)
30. Thompson, K E., "Teaching PDE-Based Modeling to ChE Undergraduates: Overcoming Conceptual and Computational Barriers," *Chem. Eng. Ed.*, **34**(2), 146 (2000)
31. Keith, J.M., F.A. Morrison, and J.A. King, "Finite Element Modules for Enhancing Undergraduate Transport Courses: Applications to Fuel Cell Fundamentals," *Proceedings* of the 2007 ASEE Annual Conference & Exposition, ASEE (2007)
32. Goldstein, A.S., "A Computational Model for Teaching Free Convection," *Chem. Eng. Ed.*, **38**(4), 272 (2004)
33. Binous, H., "Gas Permeation Computations with Mathematica," *Chem.*

Eng. Ed., **40**(2), 140 (2006)
34. Subramanian, V.R., "Computer-Facilitated Mathematical Methods in ChE Similarity Solution," *Chem. Eng. Ed.*, **40**(4), 307 (2006)
35. Keffer, D.J., A. Newman, and P. Adhangale, "Using Molecular-Level Simulations to Determine Diffusivities," *Chem. Eng. Ed.*, **37**(2), 156 (2003)
36. Kofke, D., "Molecular Modeling Task Force Update," Presented at the American Institute of Chemical Engineers Annual Meeting, 2008
37. Minerick, A.R., "A Desktop Experiment Module: Heat Transfer," *Proceedings* of the 2009 ASEE Annual Conference & Exposition, ASEE, (2009)
38. Coker, D.T., R. Prabhakar, and B.D. Freeman, "Tools for Teaching Gas Separation Using Polymers," *Chem. Eng. Ed.*, **37**(1), 60 (2003)
39. Freeman, B. Membrane Research at the University of Texas at Austin, <http://membrane.ces.utexas.edu>, accessed April 2010
40. Zheng. H., and J.M. Keith, "Web-Based Instructional Tools for Heat and Mass Transfer," *Proceedings* of the 2007 ASEE Annual Conference & Exposition, ASEE (2003)
41. Zheng, H., and J.M. Keith, "JAVA-Based Heat Transfer Visualizaiton Tools," *Chem. Eng. Ed.*, **38**(4), 282 (2004)
42. Keith, J.M., Java Web Tools: Heat and Mass Transfer Fundamentals, <http://www.chem.mtu.edu/~jmkeith/webtools/>, accessed April 2010
43. Flynn, A.M., M.H. Naraghi, and S. Shaefer, "Greening a Design-Oriented Heat Transfer Course," *Chem. Eng. Ed.*, **39**(3), 216 (2005)
44. Flynn, A.M., "Assessing the Incorporation of Green Engineering Into a Design-Oriented Heat Transfer Course," *Chem. Eng. Ed.*, **39**(4), 320 (2005)
45. Allen, D.T., and D.R. Shonnard, *Green Engineering—Environmentally Conscious Design of Chemical Processes*, Prentice-Hall (2002)
46. Green Engineering website, <http://www.rowan.edu/greenengineering>, accessed April 2010
47. Shonnard, D.R., and P.A. Deshpande, "Column Transport Experiments for Dissolved Pollutants and Colloids," *Chem. Eng. Ed.*, **35**(3), 222 (2001)
48. Farrell, S., and R. Hesketh, "An Introduction to Drug Delivery for Chemical Engineers," *Chem. Eng. Ed.*, **36**(3), 198 (2002)
49. Smart, J.L., "Optimum Cooking of French-Fry-Shaped Potatoes: A Classroom Study of Heat and Mass Transfer," *Chem. Eng. Ed.*, **37**(2), 142 (2003)
50. Davis, R.A. "A Project to Design and Build Compact Heat Exchangers," *Chem. Eng. Ed.*, **39**(1), 38 (2005)
51. Hohn, K.L., "The Chemical Engineering Behind How Carbonated Beverages Go Flat: A Hands-On Experiment for Freshmen Students," *Chem. Eng. Ed.*, **41**(1), 14 (2007)
52. Madihally, S.V., and R.S. Lewis., "Implementation and Analysis of Hemodialysis in the Unit Operations Laboratory," *Chem. Eng. Ed.*, **41**(1), 65 (2007).
53. CM3120 Transport / Unit Operations 2 "Transport Primer", available online at: http://www.chem.mtu.edu/~jmkeith/cm3120/cm3120ode.pdf, accessed May 2010
54. CM3120 Transport / Unit Operations 2 Listing of Typical Values for Engineering Unit Operations and Fluid Properties, available online at: http://www.chem.mtu.edu/~jmkeith/cm3120/cm3120rulesofthumb.pdf, accessed May 2010
55. Woods, D.R., *Rules of Thumb in Engineering Practice*, Wiley-VCH, (2007)
56. Fogler, H.S., *Elements of Chemical Reaction Engineering*, Prentice-Hall, 1st Ed. (1986)
57. Keith, J.M., "Turkey Oven Design Problem," in Kutz, M., *Heat-Transfer Calculations*, McGraw-Hill (2006)
58. Martinez-Urreaga, J., J. Mira, and C. Gonzalez-Fernandez, "Introducing the Stochastic Simulation of Chemical Reactions Using the Gillespie Algorithm and MATLAB," *Chem. Eng. Ed.*, **37**(1), 14 (2003)
59. Fan, L.T., A. Argoti, S. Caicedo, T. Chou, and W.-Y. Chen, "Stochastic Modeling of Thermal Death Kinetics in a Cell Population," *Chem. Eng. Ed.*, **37**(3), 228 (2003)
60. Lawrence, B.J., J.D. Beene, S.V. Madihally, and R.S. Lewis, "Incorporating Nonideal Reactors in a Junior-Level Course Using Computational Fluid Dynamics (CFD)," *Chem. Eng. Ed.*, **38**(2), 136 (2004)
61. Madeira, L.M., M.A. Alves, and A.E. Rodrigues, "Teaching Nonideal Reactors with CFD Tools," *Chem. Eng. Ed.*, **38**(2), 154 (2004)
62. Bakker, A., A.H. Haidari, and E.M. Marshall, "Design Reactors via CFD," *Chem. Eng. Progr.*, **97**(12), 30 (Dec. 2001)
63. Parulekar, S.J., "Numerical Problem Solving Using Mathcad in Undergraduate Reaction Engineering," *Chem. Eng. Ed.*, **40**(1), 14 (2006)
64. Wilcox, J., "Incorporating Computational Chemistry Into the ChE Curriculum," *Chem. Eng. Ed.*, **40**(4), 268 (2006)
65. Muske, K.R,. and J.A. Myers, "A Realistic Experimental Design and Statistical Analysis Project," *Chem. Eng. Ed.*, **41**(1), 31 (2007)
66. Safety and Chemical Engineering Education Program website, <http://www.sache.org>, accessed April 2010
67. Johnson, R., Chemical Reactivity Hazards website, <http://www.sache.org/files/2005/ChemReacHaz>, accessed April 2010
68. Crowl, D.A., and J.F. Louvar, *Chemical Process Safety: Fundamentals with Applications*, 2nd Ed., Prentice-Hall (2002)
69. Dartmouth College, Periodic Table Applet website, <http://www.dartmouth.edu/~chemlab/info/resources/p_table/Periodic.html>, accessed April 2010
70. Dartmouth College, Kinetics Plot Applet website, <http://www.dartmouth.edu/~chemlab/info/resources/kineticsplot/kineticsplot.html>, accessed April 2010
71. Graycie, C., Chemical Kinetics Simulator Applet website, <http://www.chem.uci.edu/undergrad/applets/sim/simulation.htm>, accessed April 2010
72. Hesketh, R.P., D. Bosak, and L. Kline, "Automotove Catalytic Reaction Experiment," *Chem. Eng. Ed.*, **34**(3), 240 (2000)
73. Shonnard, D.R., E.R. Fisher, and D.W. Caspary, "A Batch Fermentation Experiment for L-Lysine Production," *Chem. Eng. Ed.*, **37**(4), 262 (2003)
74. Li, X., X.D. Chen, and M.T. Hardin, "Investigation Into the Propagation of Baker's Yeast: A Laboratory Experiment in Biochemical Engineering," *Chem. Eng. Ed.*, **38**(3), 196 (2004)
75. Dahm, K.D., R.P. Hesketh, and M.J. Savelski, "Micromixing Experiments In the Introductory Chemical Reaction Engineering Course," *Chem. Eng. Ed.*, **39**(2), 94 (2005)
76. Rice, R.W., D.A. Bruce, D.R. Kuhnell, and C.I. McDonald, "A Kinetics Experiment for the Unit Operations Laboratory," *Chem. Eng. Ed.*, **39**(3), 238 (2005)
77. Alford, J.S., "Educating the Engineer, Part 2," *InTech*, November 2006
78. Control Station website, <http://www.controlstation.com/>, accessed April 2010
79. Cooper, D., ControlGuru: Practical Process Control e-Book website, <http://controlguru.com/>, accessed April 2010
80. Riggs, J.B., Chemical and Bio-Process Control, Ferret Publishing, Lubbock, Texas, 2007
81. Edgar, T.F., "Student to Engineer: Should the Teaching of Process Control Be Changed?" *InTech*, October 2006
82. Edgar, T.F., B.A, Ogunnaike, J.J. Downs, KR. Muske, and B.W. Bequette, "Renovating the Undergraduate Process Control Course," *Computers in Chem. Eng.*, **30**, 1749 (2006)
83. Moor, S.S., and P.R. Piergiovanni, "Inductive Learning in Process Control," *Proceedings* of the 2004 ASEE Annual Conference & Exposition, ASEE (2004)
84. Silverstein, D.L., and G. Osei-Prempeh, "Making a Chemical Process Control Course an Inductive and Deductive Learning Experience," *Chem. Eng. Ed.*, **44**(2), 119 (2010)
85. Henry, J., and R. Zollars, "Introducing Reality Into Process Control Classes," *Proceedings* of the 2005 ASEE Annual Conference & Exposition, ASEE, (2005)
86. Young, B.R., J.H. van der Lee, and W.Y. Svrcek, "A Nonlinear, Multi-Input, Multi-Output Process Control Laboratory Experiment," *Chem. Eng. Ed.*, **40**(1), 54 (2006)

87. Rusli, E., S. Ang, and R.D. Braatz, "A Quadruple-Tank Process Control Experiment," *Chem. Eng. Ed.*, **38**(3), 174 (2004)
88. Long, C.E., C.E. Holland, and E.P. Gatzke, "Experimental Air-Pressure Tank Systems for Process Control Education," *Chem. Eng. Ed.*, **40**(1), 24 (2006)
89. Muske, K.R., "Simulation and Experiment in an Introductory Process Control Laboratory Experience," *Chem. Eng. Ed.*, **37**(4), 306 (2003)
90. Marlin, T., McMaster University Process Control Education website, <http://www.pc-education.mcmaster.ca/>, accessed April 2010
91. Hough, M., E. Wood, W.S. Yip, and T. Marlin, "A Web Site to Support Active Student Learning in Process Control," *Proceedings* of the 2002 ASEE Annual Conference & Exposition, ASEE (2002)
92. Henry, J., Resource Center for Engineering Laboratories on the Web, <http://chem.engr.utc.edu/>, accessed April 2010
93. Cooper, D.J., D. Dougherty, and R. Rice, "Building Multivariable Process Control Intuition using Control Station," *Chem. Eng. Ed.*, **37**(2), 100 (2003)
94. Mathworks website, <http://www.mathworks.com>, accessed April 2010
95. Rives, C., and D.J. Lacks, "Teaching Process Control with a Numerical Approach Based on Spreadsheets," *Chem. Eng. Ed.*, **36**(3), 242 (2002)
96. Riggs, J.B., Software for Chemical Process Control, <http://www.che.ttu.edu/pcoc/software>, accessed April 2010
97. Seay, J.R., D.L Silverstein, and J.L. Smart, "Organizing and Multidisciplinary Student Design Project through An Innovative Partnership with Local Industry", Presented at the 2009 AIChE Annual Meeting, Nashville, Tennessee, November 2009
98. Baker, J.R., D.L. Silverstein, and J. Benson, "A Multi-Institutional Interdisciplinary Distance Controls Experiment: Bringing Engineering and Engineering Technology Students Together," *Proceedings* of the 2002 ASEE Annual Conference & Exposition, ASEE (2002)
99. Foster, J., and A. Heeney, "The Engineering Science Praxis Sequence: Challenges and Opportunities When Integrating Sustainable Development into the Engineering Classroom," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
100. Seay, J.R., and M.R. Eden, "Incorporating Risk Assessment and Inherently Safer Design Practices into Chemical Engineering Education," *Chem. Eng. Ed.*, **42**(3), 141 (2008)
101. Dai, L.L., " Incorporating Six Sigma Methodology Training into Chemical Engineering Education," *Chem. Eng. Ed.*, **41**(1), 53 (2007)
102. Biegler, L.T., I.E. Grossman, and A.W. Westerberg, *Systematic Methods of Chemical Process Design*, Prentice Hall International Series in the Physical and Chemical Engineering Sciences (1997)
103. Cussler, E.L., and G.D. Moggridge, *Chemical Product Design*, Cambridge University Press (2001)
104. Newell, J., K. Dahm, R. Harvey, and H. Newell, "Developing Metacognitive Engineering Teams, *Chem. Eng. Ed.*, **38**(4), 316 (2004)
105. Lumsdaine, E., J. Loukus, J. Dreyer, S. Chenoweth, and M. Lumsdaine, "Forming and Managing Project Teams in a Large Capstone Design Course," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
106. Dannels, D.P., C. Anson, L.G. Bullard, and S.W. Peretti, "Challenges in Learning Communication Skills in Chemical Engineering," *Communication Ed.*, **52**(1), 50 (2003)
107. Suraishkumar, G.K., "Improving Coherence in Technical Writing," *Chem. Eng. Ed.*, **38**(2), 116 (2004)
108. Seider, W.D., J.D. Seader, D.R. Lewin, and S. Widagdo, *Product and Process Design Principles: Synthesis, Analysis, and Evaluation*, John Wiley, 3rd Ed. (2009)
109. Ohland, M.W., S.A. Frillman, G. Zhang, C.E. Brawner, and T.K. Miller, "The Effect of an Entrepreneurship Program on GPA and Retention," *J. Eng. Ed.*, **93**(4), 193 (2004)
110. Deneen, S., "Seize the Day," *Success*, 57, Sept. 2009
111. Baker, J., M. Yoder, B. Black, R. Throne, and W. Kline, "Scorecards: Tracking Progress in Senior Design Project Courses," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
112. Rogge, R., K.C. Dee, and G. Livesay, "Development of an Evaluation for Assessing Student Practices, Independence, and Responsibility in Design Courses," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
113. Davis, D., P. Thompson, and S. Beyerlein, "Web-Based Assessment of Capstone Engineering Design," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
114. Davey, R., and J. Garside, *From Molecules to Crystallizers: An Introduction to Crystallization*, Oxford (2000)
115. Rhodes, M., *Introduction to Particle Technology*, 2nd Ed., John Wiley (2008)
116. Wibowo, C., and K.M. Ng, "Operational Issues in Solids Processing Plants: Systems View," *AIChE J.*, **47**(1), 107 (2001)
117. Hill, P.J., and K.M. Ng, "Simulation of Solids Processes Accounting for Particle Size Distribution," *AIChE J.*, **43**(3), 715 (1999)
118. Turton, R., R.C. Bailie, W.B. Whitning, and J.A. Shaeiwitz, *Analysis, Synthesis and Design of Chemical Processes*, Prentice Hall International Series in the Physical and Chemical Engineering Sciences, 3rd Ed. (2009)
119. Design Projects. West Virginia Department of Chemical Engineering. <http://www.che.cemr.wvu.edu/publications/projects/index.php>, accessed April 2010
120. Shaeiwitz, J.A., and T. Turton, "Design Projects of the Future," *Chem. Eng. Ed.*, **40**(2), 88 (2006)
121. Shaeiwitz, J.A., and T. Turton, "Chemical Product Design," *Chem. Eng. Ed.*, **35**(4), 280 (2001)
122. Peters, M.S., K.D. Timmerhaus, and R.E. West, *Plant Design and Economics for Chemical Engineers*, McGraw Hill, 5th Ed. (2003)
123. Weiss, B., and M.J. Castaldi, "A Tire Gasification Senior Design Project that Integrates Laboratory Experiments and Computer Simulation," *Chem. Eng. Ed.*, **40**(3), 203 (2006)
124. Benyahia, F., "VCM Process Design: An ABET 2000 Fully Compliant Project," *Chem. Eng. Ed.*, **39**(1), 62 (2005)
125. Hernandez, R., T. Jeffreys, A. Marwaha, and M. Thomas, "Plant Design Project: Biodiesel Production Using Acid-Catalyzed Transesterification of Yellow Grease," *Chem. Eng. Ed.*, **40**(3), 215 (2006)
126. AIChE. National Student Design Competition. <http://www.aiche.org/Students/Awards/NationalStudentDesignIndividual.aspx>, accessed April 2010
127. World Congress of Chemical Engineering. SNC-Lavelin Plant Design Competition. <http://www.wcce8.org/prog_student_snclav.html>, accessed April 2010
128. NASA. Microgravity University. ,<http://microgravityuniversity.jsc.nasa.gov>, accessed April 2010
129. Kundu, S., and M.W. Fowler, "Use of Engineering Design Competitions," *Chem. Eng. Ed.*, **43**(2), 131 (2009)
130. Redekopp, M., C. Raghavendra, A. Weber, G. Ragusa, and T. Wilbur, "A Fully Interdisciplinary Approach to Capstone Design Courses," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
131. Silverstein, D., "Improving Student Learning by Encouraging Reflection through Class Wikis," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
132. Hadley, K.R., and K.A. Debelak, "Wiki Technology as a Design Tool for a Capstone Design Course," *Chem. Eng. Ed.*, **43**(3), 194 (2009)
133. Cadwell, K., G. Zenner, N. Chesler, and W. Crone, "Developing Undergraduate Students' Design Skills Using On-Line Video Modules and Active-Learning Exercises," *Proceedings* of the 2009 Annual Conference & Exposition, ASEE (2009)
134. National Academy of Engineering. On-Line Ethics Center. <http://www.onlineethics.org/>, accessed April 2010

See* "Ideas to Consider," *continued on page 298

Evaluating the Performance of a Battery
USING TEMPERATURE AND VOLTAGE PROFILES AND A BATTERY-RESISTOR CIRCUIT MODULE

BRYAN SAWYER, MICHELLE JI, MICHAEL J. GORDON, AND GALEN J. SUPPES
University of Missouri • Columbia, MO 65211

The chemical engineering field of study is undergoing changes with goals of introducing design earlier in the curriculum and increasing use of experiential learning throughout the curriculum.[1] A modular battery experiment has been developed and used in a sophomore-level mass and energy balance course and a junior-level measurements lab, toward these goals. These experiments assess the students' ability to use the techniques, skills, and modern engineering tools necessary for engineering practice, and also allow them to demonstrate their ability to design and conduct experiments, and to analyze and interpret data.[2]

An additional goal of this module is to introduce chemical engineering students to battery technology since batteries will play the pivotal role in energy security of modern societies. As an alternative to petroleum, batteries can be used in hybrid electric vehicles (HEVs) and plug-in HEVs to displace petroleum and increase the efficiency with which limited petroleum resources are consumed. Alkaline manganese–zinc batteries are the most convenient primary batteries as the source of power for portable electronic and electric appliances.[3] For advanced devices, alkaline MnO_2–Zn batteries are preferred, which use electrolytic manganese dioxide (EMD) and an alkaline electrolyte (KOH).[4] When used with the electric grid, batteries are able to enhance technologies related to wind power, solar power, and peak load shifting.[5] These topics provide students with exceptional platforms to which they can relate their investigations to contemporary issues.

The battery-resistor circuit module allows heat transfer, mass transfer, reactions, circuit theory, heat/mass balances, and product design to be studied in a single module. The module also provides a good preparation for the study of sensors, biosensors, and instrumentation because of its integrated approach using MATLAB, LabVIEW data acquisition systems, and virtual instruments—which incorporates different aspects of the engineering curriculum. Once the standardized work-

Bryan Sawyer *is a Ph.D. candidate in chemical engineering at the University of Missouri (MU) with anticipated graduation in 2010. He received his B.S. in chemical engineering at MU in 2006.*

Michelle Ji *is an M.S. candidate in chemical engineering at MU with anticipated graduation in 2011. She received her B.S. in biological engineering at MU in 2009.*

Michael J. Gordon *is a Ph.D. candidate in chemical engineering at MU with anticipated graduation in 2011. He received his B.S. in chemical engineering at MU in 2009.*

Galen Suppes *is a professor of chemical engineering at the MU and has participated in several capacities in the AIChE Student Chapters committees that organizes the AIChE Design Contest Subcommittee. Professor Suppes received the 2006 Green Chemistry Challenge Award for academia. He received his B.S. from Kansas State University and his Ph.D. from The Johns Hopkins University.*

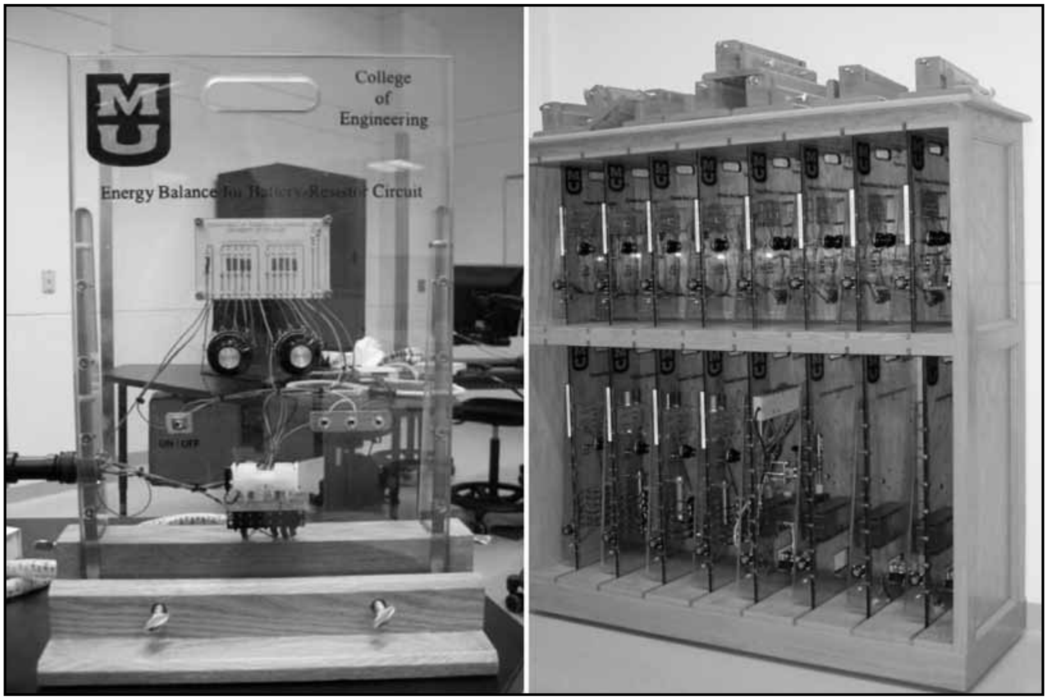


Figure 1. *Photograph showing the Energy Balance for Battery-Resistor Circuit Module (left) connected to the data acquisition system cable and module storage cabinet (right) that is used to store 16 modules and mounting bases.*

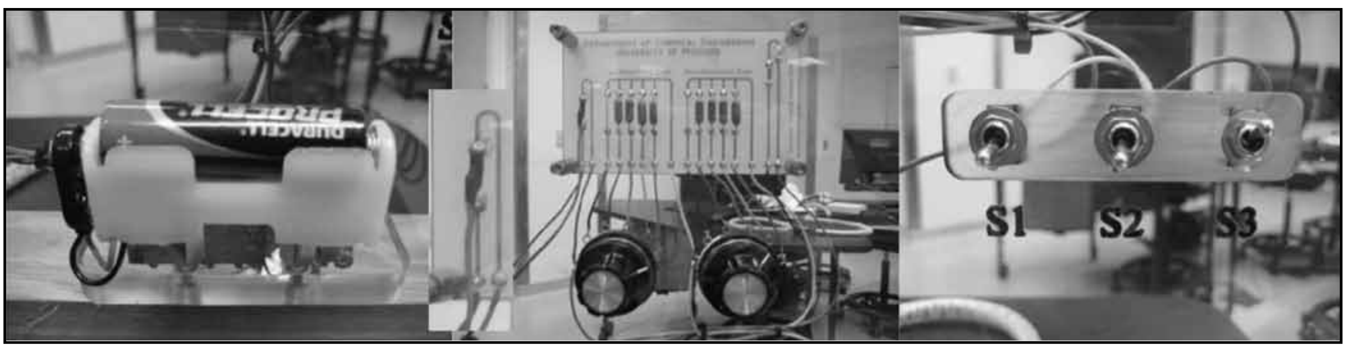


Figure 2. *Close-up images of module, including, from left to right: AA battery holder; expanded image of 1-ohm resistor with thermocouple attached with shrink wrap; circuit board with 1-ohm resistor, two resistor banks, and knobs for selecting resistance from two resistor banks; and switches used to select locations for voltage measurements.*

stations, stands, and storage are in place, individual modules can be produced for a few hundred dollars with four modules occupying about two square feet of space when stored in the storage cabinet.

APPARATUS

Figure 1 shows the experimental module composed of circuitry mounted on a 1 cm thick Lexan panel. The panel and reinforcing bases are mounted on an oak base. A cabinet allows compact storage of 16 modules and mounting bases. Each module connects to a computer workstation equipped with a National Instruments data acquisition card (NI PCI-6259), a shielded connector block (NI SCB-68), and LabVIEW 8.6 software. Use of a standardized 24-pin connector allows different experiments to use the same connector interface and respective workstation.

Figure 2 provides close-up images of the AA battery connector, resistor bank, and voltages switches. A small thermocouple embedded in the AA battery holder monitors the battery temperature, which is used for the energy balance.

A second thermocouple is attached to the 1-ohm resistor—the temperature profile of the 1-ohm resistor is the key measurement for the energy balance studies. The 1-ohm resistor is connected in series with two other resistors from two resistor banks as selected by the selector switches. Each selector switch has five settings allowing 25 different loads to be measured. These resistor banks allow variations in an assignment to be made so no two groups or individuals have the same exact experiment. This allows the students to compare their data with other individuals or groups to relate the effect of the changes in resistor load, promoting a more interactive learning environment.[6]

A series of three switches allows students to measure voltages at different locations in the circuit. Figure 3 provides a schematic of the battery (represented as a voltage source and internal resistance), the two resistor banks with the two associated selector-switches, and the three switches that allow voltages to be measured over the different loads.

Operating the module consists of the following steps:

1. *Insert and fasten the module on a base at a workstation and connect the 24-pin connector that links the module to the National Instruments based data acquisition system.*
2. *Place AA battery in the battery holder or connect ancillary battery to system.*
3. *Start module-specific LabVIEW virtual instrument file (VI).*
4. *Set module selector switches (N1 and N2) to provide experiment-specific resistance, put S1 and S2 in the down position and S3 in the up position to measure voltage across entire load.*
5. *Hit the start button on LabVIEW VI followed by switching the module on using the module's on/off switch.*
6. *Record data for the desired time (typically 5-10 minutes) and then click on the LabVIEW VI "STOP" button.*
7. *Return module switch to the off position and either repeat or disassemble the experiment.*

Data files created by LabVIEW are readily accessible by MS Excel and include columns of time, resistor temperature, battery temperature, and voltage (as selected by the switch settings). The first time the experiment is run by a group, it takes about 25 minutes. Subsequent runs take about 10-15 minutes. Typical errors of experiments include use of depleted batteries or operating experiments with switches in the wrong positions. The modules are available in an open-format laboratory for 45 hours a week in an environment that better resembles a computer workstation lab than a chemical engineering lab. Students are performing experiments (experiential learning) side-by-side with students performing homework and writing reports.[7]

This paper explains three different experiment-based projects that can be performed using this module.

PROJECT 1: BATTERY-RESISTOR ENERGY BALANCE

The purpose of the Mass and Energy Balance Experiment is to predict and then model the transient temperature profile of the 1-ohm resistor that is connected in series with two resistor banks and an AA battery. The students are given minimal guidance in the initial prediction of the temperature profile beyond a schematic of the circuit, knob settings, and the specification of the brand name and type (zinc-alkaline) of battery.

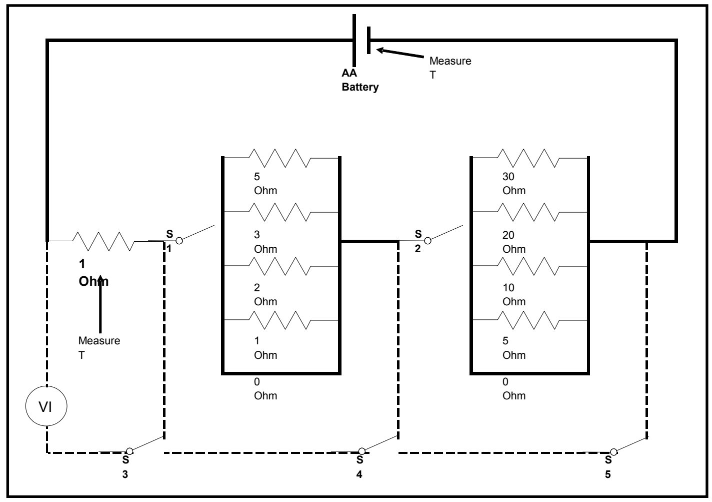


Figure 3. *Schematic of the experimental system that shows the different resistors in series and switch settings for voltage measurements.*

The students are responsible for the derivation of governing differential equations such as the equation for change in resistor temperature as a function of time, $\frac{dT_{res}}{dt}$ which can be derived from the change in internal energy over time; $\frac{dU}{dt}$.[8] The students are to identify how voltage drop and amperage translate to a heat input term in a first law balance, and they are to estimate parameters such as heat capacity and mass. They are encouraged to use MatLab to solve the differential equations that govern the system.

The following are pertinent governing equations:

$$\frac{dU}{dt} = Q - W \tag{1}$$

$$\frac{m_{res} C_{res} dT_{res}}{dt} = Q - W \tag{2}$$

$$\frac{m_{res} C_{res} dT_{res}}{dt} = V^2 / R - hA\left(T_{res} - T_{ambient}\right) \tag{3}$$

During initial predictions the students will typically neglect the convective cooling of the resistor by ambient air or they will struggle to identify how to model the heat transfer. Most students have not had a course in heat transfer, and when they identify the need to apply an engineering science that they have not yet covered they are directed to research the use of heat transfer coefficients.[9] The need to take into account the convective heat transfer term to model the temperature profile of the resistor will become evident when they obtain experimental temperature profiles. If convection was not identified during the predictive modeling stage of the project, the temperature profile indicates the need to modify the model battery. The modeling process provides a conceptual learning element because the students can visually relate how changing the heat transfer coefficients modifies the temperature profile.[2]

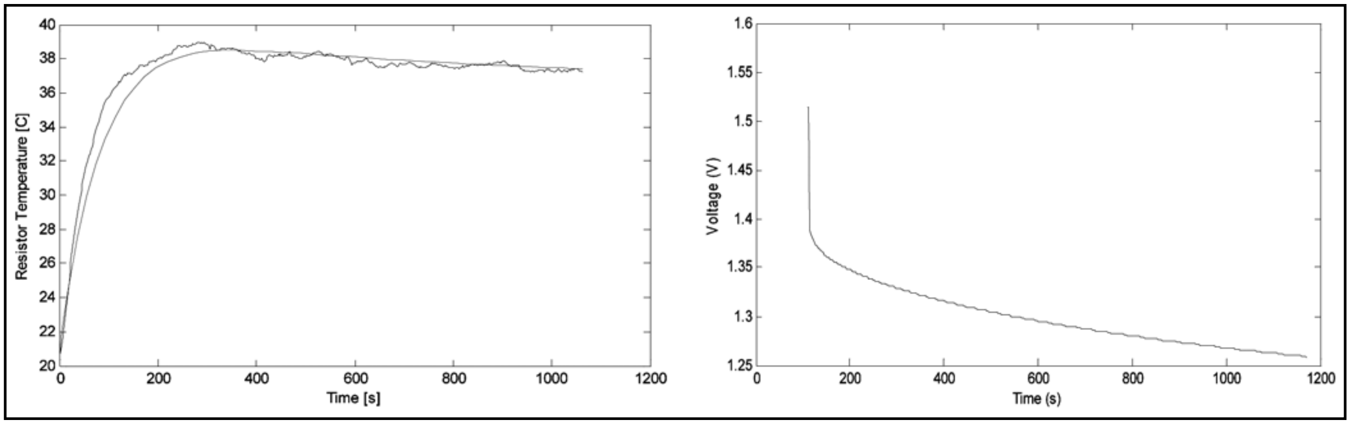


Figure 4. A plot of the resistor temperature with superimposition of modeling results (left) and voltage profile of the battery operating with a 3-ohm total resistor (right). For voltage profile plot the experiment was initiated at t=100 s.

Figure 4 provides a typical resistor temperature vs. time profile and a voltage profile for battery discharge operating with a 3-ohm total resistance load.

The resistor temperature vs. time profile can be used to model the resistor temperature as a function of time by manipulating hA, the heat transfer coefficient, and mC, the heat capacity, in the MATLAB program. The decreasing temperature is a manifestation of decreasing voltage power output from the AA battery, which is under a heavy load.[10] This aspect of the project introduces the challenge of how to handle the modeling of the resistor temperature for a non-constant voltage term—this introduces the utility for numerical solution of ordinary differential equations when analytical solutions may not be an option.[11]

Another aspect of this lab can be used to measure battery efficiency by measuring actual voltage, shown in Figure 4, delivered by the battery divided by the ideal voltage. The students will be able to follow the temperature profile of the battery and visually understand and verify what happens to the lost energy.[12]

For semester-long projects, the students are able to sequentially perform the following:

1. *Convert the voltage profile of Figure 4 to battery efficiency vs. time.*
2. *Obtain battery voltages at a specified times (*e.g.*, 30 seconds into discharge) over multiple resistances then use these data to prepare a battery performance curve (Voltage vs. Amperage).*
3. *Fully deplete a battery to obtain the amp-hours of energy the battery is able to deliver and compare this to the mass of the battery components (as estimated based on Material Safety Data Sheet (MSDS) information).*
4. *Use the performance curve (from Reference 2), amount of active reagent utilization (from Reference 3), and membrane surface area (membrane that separates cathode from anode, an estimated value) to design a battery for a different application (*e.g.*, powering a 20 W light bulb for 2 hours).*

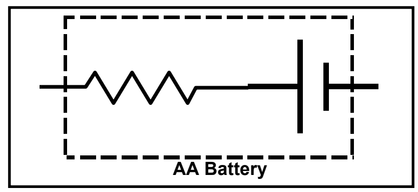


Figure 5. Schematic of a battery as a voltage source in series with an internal resistance.

A project based on these steps provides a valuable experiential learning process involving: energy balances, transient energy balances, basic circuit theory, modeling vs. predictive simulation, convective heat transfer, analytical vs. numerical solution methods, mass balances, transient mass balances, battery performance curves, and product design.[13]

PROJECT 2: EVALUATING THE INTERNAL RESISTANCE OF A BATTERY

A common representation of a battery in circuit theory is as a resistor in series with a voltage source (see Figure 5). The goal of this project is to identify the utility and accuracy of this commonly used model for a battery in a circuit. In the first phase of this experiment, the students evaluate an AA battery identifying the voltage at 10 seconds for each of several module-set resistances (from high to low).

Analysis of the data for this project can be obtained by linear regression of an equation derived as follows.[14] Where:

$$V_o = I\left(R_{Battery} + R_{Circuit}\right) \tag{4}$$

The current (I) for each experiment can be identified by this same equation evaluated over the circuit load rather than the theoretical voltage of the battery:

$$I = V_{Circuit} / R_{Circuit} \tag{5}$$

or

$$V_{Circuit} = V_o - R_{Battery}\left(V_{Circuit} / R_{Circuit}\right) \tag{6}$$

where linear regression can be used to identify V_O (constant) and $R_{Battery}$ (slope).

Figure 6 illustrates experimental data plotted according to Eq. (6) with an excellent correlation and little scatter. The students are expected to analyze their data and understand why the internal resistance of the battery stays constant, using equations to justify their results. The internal resistance of the battery is relatively constant for data taken at a constant time of exposure to a load. For low resistances, the resistance of the battery will decrease with time due to increased diffusion over-potential as the substrates closest to the membrane are consumed.[15] This trend is seen for the right-most data point, and for this reason, the linear regression was performed without including that data point.

Extensions of this project could include evaluating the internal battery resistance at different times the battery is under load.[16] Detailed discussions related to transient diffusions in packed-bed anodes could be used to explain the dependence of the internal battery resistance on time. If the students are able to do the sophisticated modeling, the diffusion in the packed bed could be modeled, converted to diffusion over-potential, and interpreted in terms of a resistor model.

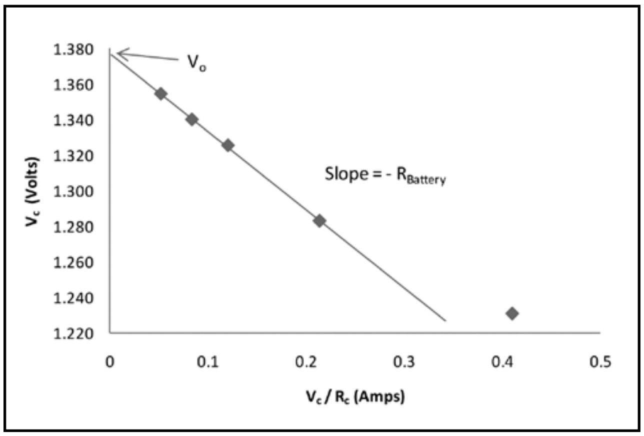


Figure 6. *Example results from PROJECT 2 and Eq. (6) for evaluating the internal resistance of a battery. The data are for different circuit resistances evaluated with the experimental module.*

PROJECT 3: DIFFUSION AND PERMEABILITY IN MANGANESE DIOXIDE- ZINC BATTERY

The objective of this project is to evaluate batteries that the students assemble. The students are also to relate fundamental differences of the battery performances to properties of the materials and the cell geometry, and to quantitatively correlate the performance to diffusivity resulting from varying the separator material. The use of a zinc electrode anode is important because of its high open-circuit voltage in the KOH electrolyte, a low corrosion rate, and a low material cost.[17]

A schematic of the battery assembly is provided by Figure 7. Prepared anode packing, cathode packing, separator materials, and premixed electrolyte are provided to the students for assembling the batteries. The electrode packings are volumetrically dispensed into the cell being separated by the separator materials. Alligator clips are used to connect the current collectors of the battery assembly to the AA battery holder points of contact on the experimental module.

The experimental procedures include assembling several Zn-MnO_2 batteries with different separator materials and evaluate the performance in a 33-ohm circuit. Zinc powder is used as the anode packing in preference to zinc foil or plates because of its large surface area to distribute solid and liquid phases more homogeneously.[18] A high zinc surface-area-to-volume ratio is needed for high-rate capability and since zinc oxide will form on the surface of the zinc as summarized by the following half reactions:[19]

$$Zn(s) + 2OH^-(aq) \rightarrow ZnO(s) + H_2O(l) + 2\bar{e} \qquad (7)$$

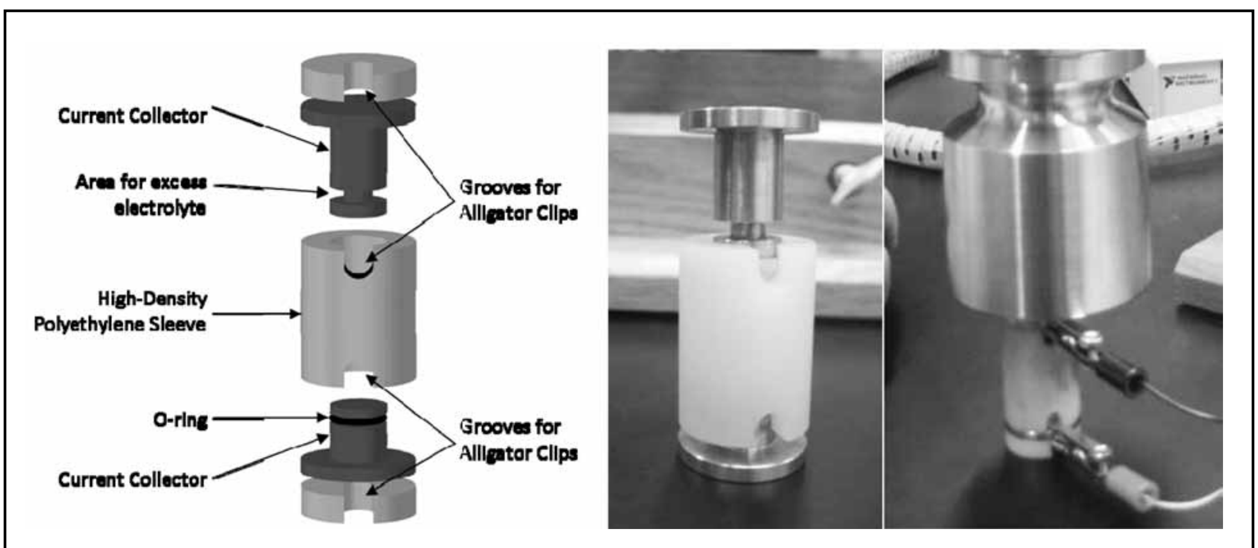


Figure 7. *Pictorial representation of a compression cell used for the assembly of MnO_2 – Zn batteries (left) with picture of assembled cell (middle) and an assembled cell with weight to provide compression (right).*

$$2MnO_2(s) + H_2O(l) + 2\bar{e} \rightarrow Mn_2O_3(s) + 2OH^-(aq) \quad (8)$$

Manganese oxide powder mixed with a carbon black is used as the cathode. The carbon is used to increase conductivity of the positive active mass to reduce the internal resistance of the cell.[20] This material may require mechanical processing to maximize reactivity.[21] Potassium hydroxide (1M or 2M) in distilled water works well as the electrolyte because of its high conductivity, and results in a low internal resistance.[22] In the presence of KOH, the discharge behavior of MnO_2 occurs in a heterogeneous phase reaction.[23]

The separator materials provide the best opportunity to systematically vary a parameter that impacts battery performance. Sheets of permeable material can be punched to sizes that match the inner diameter of the battery's polyethylene sleeve. When preparing the battery, care must be taken to assure that the permeable separator totally separates the anode from the cathode or the battery will short circuit. Filter paper works well as a separator with the experimental parameter being the number of sheets of filter paper placed between the anode and cathode. The filter paper used in this experiment is a qualitative type with coarse porosity and a fast flow rate, from Fisher Brand. More sheets will create greater resistance to diffusion and greater over-potential losses.[15] It is also beneficial to have a negative control of a non-permeable polypropylene membrane to confirm that in the absence of a diffusive path between the anode and cathode, the battery voltage will immediately go to zero.

The test cell (Figure 7) is basically a compression cell composed of two pistons inside a nonconductive sleeve. The battery is assembled by inserting the base of the compression cell first (the shorter piston). It is assembled as follows:

1. *Place a volumetrically dispersed amount of the cathode material (MnO_2) into the cylinder (enough to cover a thin layer on the bottom of the cell) and tap the cell to create an even distribution.*
2. *Cover the material with the correct number of filter papers (qualitative P8 Fisher Brand).*
3. *Wet the filter paper by placing a few drops of the electrolyte solution (~10-15 drops of 1M KOH).* Potassium Hydroxide is used as an electrolyte in Manganese Dioxide-Zinc batteries because of its strong conductivity.
4. *Add a thin layer of the anode material (Zn) and close the compression cell with the longer piston.*
5. *Bring the assembled battery back to the module and obtain a pair of wires. Remove the original AA battery, snap off the battery power adapters and connect them to the wires.*
6. *Attach the alligator clips to the assembled battery and put the two plastic pieces on the top and bottom of the assembled battery, aligning them with the notches.*
7. *Place a 6 kg weight on the assembled battery and run the program. The weight on the battery compresses the anode and cathode material together, making the electrons flow more efficiently, and creates a better voltage.*[24]

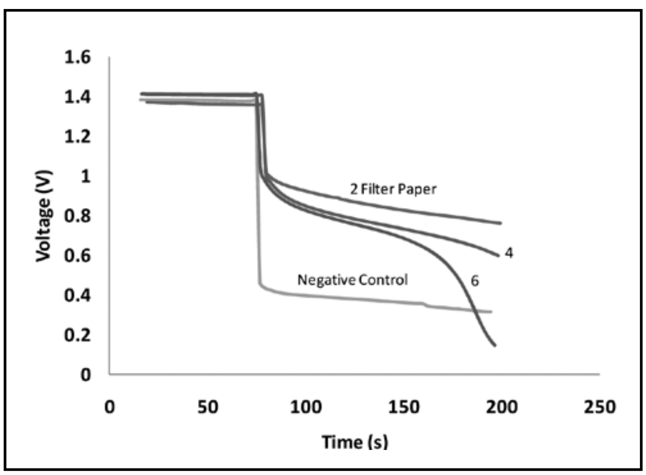


Figure 8. *Graph of results showing proposed trend of decreasing voltage with increasing resistance of separator between electrodes. The numbers indicate the number of layers of filter paper between the electrodes.*

Figure 8 summarizes representative data for a study of 2, 4, and 6 layers of filter paper, and a negative control using polypropylene as a nonpermeable membrane separating the anode material from the cathode material, keeping the time of the experimental runs constant. The polypropylene membranes used in this experiment were obtained using the same hole-punch technique as the filter papers, using a petri dish as the material. Battery performance typically consists of a steep drop in voltage initially and then a steady decline. At a constant load, an increase in resistance (more layers of filter paper) results in a lower voltage delivered to the resistor.[15] Ideally, the voltage for the nonpermeable membrane should immediately drop to zero; however, because of the difficulties involved in constructing a perfect separation seal, there may be some voltage detected due to the seepage and mixing of the anodic and cathodic material around the outer perimeter of the polypropylene membrane.

The students should be able to qualitatively understand how increased diffusion distances through permeable materials translate to increased voltage over-potentials.[15] In more advanced applications, the permeability can be related to voltage. Other variations from this experiment include use of battery assemblies with different inner diameters and use of non-permeable separators cut into washer-shapes that vary the cross-sectional area available for diffusion.

STUDENT FEEDBACK

For Project 1, the students recognized and appreciated how energy is converted from chemical to thermal forms and how transient differential models can relate underlying engineering science (Ohm's law, convective heat transfer) to observed phenomena. The most frequent problem encountered was a lack of attention by the students to which voltages were actually being measured during the experiment. Project 2 was a simple and straightforward experiment that validates a commonly used model for batteries. Students who expected the need for a detailed analysis based on differential equations were disappointed. Project 3 was effective in getting students to contemplate some more complicated aspects of mass transfer and how mass transfer limits the performance of a battery. The primary concern with Project 3 was that sloppy preparation of the assembled battery could result in inconsistent data.

SUMMARY

The battery provides an excellent basis for student projects in chemical engineering. The module described in this paper provides a way to deliver experiential learning with batteries in open formats that can be used with a variety of lecture-based courses. The students are able to directly connect with what they observe in the experiential learning because they encounter and frequently use batteries in their day-to-day routines. Different variations of battery-based projects allow students to use energy balances, transient energy balances, basic circuit theory, modeling vs. predictive simulation, convective heat transfer, analytical vs. numerical solution methods, mass balances, transient mass balances, battery performance curves, and product design.

ACKNOWLEDGMENTS

The authors appreciate the support of the Chemical Engineering Department and the College of Engineering at the University of Missouri for making this work possible. The contributions of Dr. Mike Klote of MU Engineering Technical Services and kind contributions of MU alumnus Dr. Robert Healy from classes of 1964 and 1968, are greatly appreciated.

REFERENCES

1. Rugarcia, A., R.M. Felder, D.R. Woods, and J.E. Stice, "Future of Engineering Education. I. A Vision for a New Century," *Chem. Eng. Ed.*, **34**(1) 16 (2000)
2. Felder, R.M., and R. Brent, "Designing and Teaching Courses to Satisfy the ABET Engineering Criteria," *J. Eng. Ed.*, **92**(1), 18 (2003)
3. Takamura, T., "Primary Batteries: Aqueous Systems–Alkaline Manganese–Zinc," in *Encyclopedia of Electrochemical Power Sources*, Elsevier (2009)
4. Kordescha, K., and W. Taucher-Mautner, "Chemistry, Electrochemistry, and Electrochemical Applications: Manganese," in *Encyclopedia of Electrochemical Power Sources*, Elsevier (2009)
5. Linden, D., and T.B. Reddy, *Handbook of Batteries*, 3rd Ed., McGraw-Hill, New York (2002)
6. Bonwell, C.C., and J.A. Eison, *Active Learning: Creating Excitement in the Classroom*, George Washington University, Washington, DC, (1991)
7. Woods, D.R., R.M. Felder, and A. Rugarcia, "Developing Critical Skills," *The Future of Eng. Ed. 2000*, **1**(3), 20 (2000)
8. Knight, R.D., *Physics for Scientists and Engineers: A Strategic Approach*, Pearson Education, San Francisco (2004)
9. Aronson, M.T., R.W. Deitcher, Y. Xi, and R.J. Davis, "New Laboratory Course for Senior- Level Chemical Engineering Students," *Chem. Eng. Ed.*, **43**(2) 104 (2009)
10. Cengel, Y.A., and M.A. Boles, *Thermodynamics—an Engineering Approach*, 5th Ed., McGraw- Hill (2005)
11. Felder, R.M., D.R. Woods, J.E. Stice, and A. Rugarcia, "Future of Engineering Education II. Teaching Methods that Work," *Chem. Eng. Ed.,* **34**(1) 26 (2000)
12. Prince, M., "Does Active Learning Work?" *J. Eng. Ed.*, **93**(9), 9 (2004)
13. Spencer, J.L., "A Process Dynamics and Control Experiment for the Undergraduate Laboratory," *Chem. Eng. Ed.*, **43**(1), 5 (2009)
14. Ott, B.J., and J. Boerio-Goates, *Chemical Thermodynamics – Principles and Applications*, Academic Press (2000)
15. Lantelme, F., H. Groulta, and N. Kumagai, "Study of the Concentration-Dependent Diffusion in Lithium Batteries," *Electrochimica Acta,* **45**(19) 3171 (2009)
16. Mitsos, A., "Design Course for Micropower-Generation Devices," *Chem. Eng. Ed.*, **43**(3), 5 (2009)
17. Yang, C.-C., and S.-J. Lin, "Improvement of High-Rate Capability of Alkaline Zn-MnO_2 Battery," *J. Power Sources*, **112**, 174-183 (2002)
18. Almeida, M.F., S.M. Xará, J. Delgado, and C.A. Costa, "Characterization of Spent AA Household Alkaline Batteries," *Waste Management*, **26**(5), 466 (2005)
19. Cahiez, G., M. Alami, R.J.K. Taylor, M. Reid, and J.S. Foot, "Manganese Dioxide," in *Encyclopedia of Reagents for Organic Synthesis*, ed. Paquette, L.A., J. Wiley & Sons, New York (2004)
20. Dell, R.M., "Batteries: Fifty Years of Materials Development," *Solid State Ionics,* **134**(1- 2), 139 (2000)
21. Walker, A., and T.F. Reise, *Process for Producing Beta Manganese Dioxide,* U.S. Patent 4921689, Duracell, Inc., 5 (1990)
22. Manickama, M., "Examining Manganese Dioxide Electrode in KOH Electrolyte Using TEM Technique," *J. Electroanalytical Chemistry*, **616**, 99-106 (2008)
23. Manickama, M., P. Singh, T.B. Issa, S. Thurgate, and R.D. Marcob, "Lithium Insertion Into Manganese Dioxide Electrode in MnO_2/Zn aqueous battery: Part I. A preliminary study," *J. Power Sources*, **130**, 254-259 (2004)
24. Brady, J.E., G.E. Humiston, and H. Heikkinen, *General Chemistry: Principles and Structure,* 3rd Ed., John Wiley & Sons (1983) ❐

An Open Letter to …

SENIORS IN CHEMICAL ENGINEERING

As a senior, you probably have some questions about graduate school. The following paragraphs may assist you in finding some of the answers.

Should you go to graduate school?

We invite you to consider graduate school as an opportunity to further your professional development. Graduate work can be exciting and intellectually satisfying, and at the same time can provide you with insurance against the ever-increasing danger of technical obsolescence in our fast-paced society. An advanced degree is certainly helpful if you want to include a research component in your career and a Ph.D. is normally a prerequisite for an academic position. Although graduate school includes an in-depth research experience, it is also an integrative period. Graduate research work under the guidance of a knowledgeable faculty member can be an important factor in your growth toward confidence, independence, and maturity.

What is taught in graduate school?

A graduate education generally includes a coursework component and a research experience. The first term of graduate school will often focus on the study of advanced-core chemical engineering science subjects (*e.g.*, transport phenomena, phase equilibria, reaction engineering). These courses build on the material learned as an undergraduate, using more sophisticated mathematics and often including a molecular perspective. Early in the graduate program, you will select a research topic and a research adviser and begin to establish a knowledge base in the research subject through both coursework and independent study. Graduate education thus begins with an emphasis on structured learning in courses and moves on to the creative, exciting, and open-ended process of research. In addition, graduate school is a time to expand your intellectual and social horizons through participation in the activities provided by the campus community.

We suggest that you pick up one of the fall issues of *Chemical Engineering Education (CEE),* whether it be the current issue or one of our prior fall issues, and read some of the articles written by scholars at various universities on a wide variety of subjects pertinent to graduate education. The chemical engineering professors or the library at your university are both good sources for borrowing current and back issues of *CEE*.

Perusing the graduate-school advertisements in this special compilation can also be a valuable resource, not only for determining what is taught in graduate school, but also where it is taught and by whom it is taught. We encourage you to carefully read the information in the ads and to contact any of the departments that interest you.

What is the nature of graduate research?

Graduate research can open the door to a lifelong inquiry that may well lead you in a number of directions during your professional life, whether you pursue it within the confines of an industrial setting or in the laboratories of a university. Learning *how* to do research is of primary importance, and the training you receive as a graduate student will give you the discipline, the independence, and (hopefully) the intellectual curiosity that will stand you in good stead throughout your career. The increasingly competitive arena of high technology and society's ever-expanding fields of inquiry demand, more than ever, trained and capable researchers to fuel the engines of discovery.

Where should you go to graduate school?

There are many fine chemical engineering departments, each with its own "personality" and special strengths. Choosing the one that is "right" for you is a highly personal decision and one that only you can make. Note, however, that there are schools that specialize in preparing students for academic careers just as there are those that prepare students for specific industries. Or, perhaps there is a specific area of research you are interested in, and finding a school or a certain professor with great strength or reputation in that particular area would be desirable. If you are uncertain as to your eventual field of research, perhaps you should consider one of the larger departments that has diversified research activity, giving you the exposure and experience to make a wise career choice later in your education. On the other hand, choosing a graduate school could be as simple as choosing some area of the country that is near family members or friends; or you may view the benefits of a smaller, more personal, department as more to your liking; or you might choose a school with a climate conducive to sports or leisure activities in which you are interested.

Many factors may eventually feed into your decision of where to go to graduate school. Study the ads in this special printing and write to or view the Web pages of departments that interest you; ask for pertinent information not only about areas of study but also about fellowships that may be available, about the number of students in graduate school, about any special programs. Ask your undergraduate professors about their experiences in graduate school, and don't be shy about asking them to recommend schools to you. They should know your strengths and weaknesses by this stage in your collegiate career, and through using that knowledge they should be a valuable source of information and encouragement for you.

Financial Aid

Don't overlook the fact that most graduate students receive financial support at a level sufficient to meet normal living needs. This support is provided through research assistantships, teaching assistantships, or fellowships. If you are interested in graduate school next fall, you should begin the application process early this fall since admission decisions are often made at the beginning of the new calendar year. This process includes requesting application materials, seeking sources of fellowships, taking national entrance exams (*i.e.*, the Graduate Record Exam, GRE, is required by many institutions), and visiting the school.

A resolution by the Council of Graduate Schools—in which most schools are members—outlines accepted practices for accepting financial support (such as graduate scholarships, assistantships, or fellowships). You should be aware that the agreed upon deadline for accepting offers of financial support for a fall-term start is April 15. The resolution states that you are under no obligation to respond to offers of financial support prior to April 15 (earlier deadlines for acceptance violate the intent of the resolution). Furthermore, an acceptance given or left in force after April 15 commits you to reject any other offer without first obtaining a written release from the institution to which the commitment has been made.

Historically, most students have entered graduate school in the fall term, but many schools do admit students for other starting dates. ❒

We hope that this special collection of chemical engineering graduate-school information proves to be helpful to you in making your decision about the merits of attending graduate school and assists you in selecting an institution that meets your needs.

INDEX ■ Graduate Education Advertisements

Graduate Education in Chemical and Biomolecular Engineering

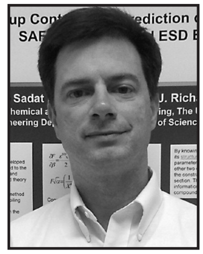
Teaching and research assistantships as well as industrially sponsored fellowships available. In addition to stipends, tuition and fees are waived. PhD students may get some incentive scholarships.

Chairman, Graduate Committee
Department of Chemical and Biomolecular Engineering
The University of Akron
Akron, OH 44325-3906
Phone (330) 972-7250
Fax (330) 972-5856
www.chemical.uakron.edu

S. S. C. CHUANG
Catalysis, Reaction Engineering, Environmentally Benign Synthesis, Fuel Cell

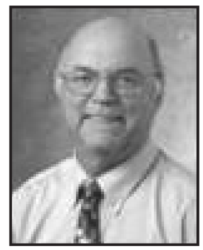
C. MONTY
Reaction Engineering, Biomimicry, Microsensors

J. R. ELLIOTT
Molecular Simulation, Phase Behavior, Physical Properties, Process Modeling, Supercritical Fluids



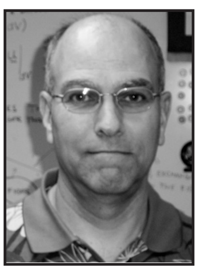
B. Z. NEWBY
Surface Modification, Alternative Patterning, AntiFouling Coatings, Gradient Surfaces

E. A. EVANS
Materials Processing and CVD Modeling
Plasma Enhanced Deposition and Crystal Growth Modeling



J. H. PAYER
Corrosion & Electrochemistry, Systems Health Monitoring and Reliability, Materials Performance and Failure Analysis

G. G. CHASE
Multiphase Processes, Nanofibers, Filtration, Coalescence



L.-K. JU
Renewable Bioenergy, Environmental Bioengineering

Department Chair

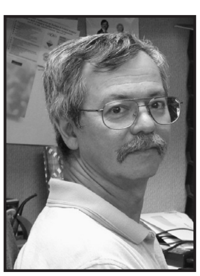
H. C. QAMMAR
Nonlinear Control, Chaotic Processes, Engineering Education

G. CHENG
Biomaterials, Protein Engineering, Drug Delivery and Nanomedicine

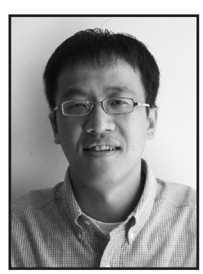
N. D. LEIPZIG
Cell and Tissue Mechanobiology, Biomaterials, Tissue Engineering

X. SHAN
Corrosion & Electrochemistry, Hydrogen Effects on Materials, Materials Performance and Life Prediction

H. M. CHEUNG
Nanocomposite Materials, Sonochemical Processing, Polymerization in Nanostructured Fluids, Supercritical Fluid Processing



L. LIU
Biointerfaces, Biomaterials, Biosensors, Tissue Engineering



J. ZHENG
Computational Biophysics, Biomolecular Interfaces, Biomaterials

THE UNIVERSITY OF
ALABAMA

Chemical & Biological Engineering

A dedicated faculty with state of the art facilities, offering research programs leading to Doctor of Philosophy and Master of Science degrees. In 2009, the department moved into its new home, the $70 million Science and Engineering Complex.

Research Areas:

Biological Applications of Nanomaterials, Biomaterials, Catalysis and Reactor Design, Drug Delivery, Electronic Materials, Energy and CO_2 Separation and Sequestration, Fuel Cells, Interfacial Transport, Magnetic Materials, Membrane Separations and Reactors, Pharmaceutical Synthesis and Microchemical Systems, Polymer Rheology, Simulations and Modeling

Faculty:

Viola Acoff (UAB)
David Arnold (Purdue)
Yuping Bao (Washington)
Jason Bara (Colorado)
Christopher Brazel (Purdue)
Eric Carlson (Wyoming)
Peter Clark (Oklahoma State)
Nagy El-Kaddah (Imperial College)
Arun Gupta (Stanford)
Ryan Hartman (Michigan)
Tonya Klein (NC State)
Alan Lane (Massachusetts)
Stephen Ritchie (Kentucky)
C. Heath Turner (NC State)
Mark Weaver (Florida)
John Wiest (Wisconsin)

For Information Contact:

Director of Graduate Studies
Chemical & Biological Engineering
The University of Alabama
Box 870203
Tuscaloosa, AL 35487-0203

(205) 348-6450
hturner@eng.ua.edu
http://che.eng.ua.edu

An equal employment/equal educational opportunity institution

Chemical and Materials Engineering

Graduate Program

Faculty and Research

R. Michael Banish; Ph.D., University of Utah
Associate Professor
Crystal growth, transport property measurements, and characterization.

Ramón L. Cerro; Ph.D., UC Davis
Professor
Theoretical and experimental fluid mechanics and physicochemical hydrodynamics.

Chien P. Chen; Ph.D., Michigan State
Professor and Chair
Lab-on-chip microfluidics, multiphase transport, spray combustion, computational fluid dynamics, turbulence modeling of chemically reacting flows and aero-optics.

Krishnan K. Chittur; Ph.D., Rice University
Professor
Biomaterials, bioprocess monitoring, gene expression bioinformatics, and FTIR/ATR.

James E. Smith Jr; Ph.D., South Carolina
Professor
Ceramic and metallic composites, catalysis and reaction engineering, fiber optic chemical sensing, combustion diagnostic of hypergolic fuels, and hydrogen storage.

Jeffrey J. Weimer; Ph.D., MIT
Associate Professor
Surface science and technology as applied to adhesion phenomena, biocompatibility, corrosion, friction, heterogeneous catalysis, sensors, and thin films.

David B. Williams; Sc.D., Cambridge
Professor and University President
Analytical, transmission and scanning electron microscopy, applications to interfacial segregation and bonding changes, texture and phase diagram determination in metals and alloys.

The Department of Chemical & Materials Engineering offers an **M.S Degree in Engineering**. A **Ph.D. Degree** is offered as a Chemical Engineering **option to the Mechanical Engineering** Ph.D. Degree and through collaborative programs in **Materials Science or Biotechnology**.

Faculty in the department have a broad range of research interests. This breadth affords graduate students unique opportunities to be on the forefront of many emerging technologies, especially in **materials or biotechnology** related areas.

The location of the UAHuntsville campus provides a strong potential for chemical engineering graduate students to apply their research to real-world problems. The campus sits near the **NASA Marshall Space Flight Center and Redstone Arsenal**. It is also in proximity to over **200 high-technology industries** that support the corresponding aerospace, weapons systems, and biotechnology demands of these agencies. The campus is also near many chemical production plants, such as for fibers, catalysts, and polymers.

Chemical and Materials Engineering
130 Engineering Building
Huntsville, Alabama 35899
Ph: 256-824-6810 Fax: 256-824-6839
http://www.uah.edu
http://www.che.uah.edu

UAHuntsville
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

FACULTY / RESEARCH INTERESTS

ROBERT G. ARNOLD, Professor (CalTech)
Microbiological Hazardous Waste Treatment, Metals Speciation and Toxicity

JAMES C. BAYGENTS, Associate Professor and Associate Dean of Engineering (Princeton)
Fluid Mechanics, Transport and Colloidal Phenomena, Bioseparations

PAUL BLOWERS, Associate Professor (Illinois, Urbana-Champaign)
Chemical Kinetics, Catalysis, Environmental Foresight, Green Design

WENDELL ELA, Professor (Stanford)
Particle-Particle Interactions, Environmental Chemistry

JAMES FARRELL, Professor (Stanford)
Sorption/desorption of Organics in Soils

JAMES A. FIELD, Professor and Chair (Wageningen University)
Bioremediation, Environmental Microbiology, Hazardous Waste Treatment

ROBERTO GUZMAN, Professor (North Carolina State)
Affinity Protein Separations, Polymeric Surface Science

ANTHONY MUSCAT, Professor (Stanford)
Kinetics, Surface Chemistry, Surface Engineering, Semiconductor Processing, Microcontamination

KIMBERLY OGDEN, Professor (Colorado)
Bioreactors, Bioremediation, Organics Removal from Soils

ARA PHILIPOSSIAN, Professor (Tufts)
Chemical/Mechanical Polishing, Semiconductor Processing

EDUARDO SÁEZ, Professor (UC, Davis)
Polymer Flows, Multiphase Reactors, Colloids

GLENN L. SCHRADER, Professor and Associate Dean of Engineering (Wisconsin)
Catalysis, Environmental Sustainability, Thin Films, Kinetics, Solar Energy

FARHANG SHADMAN, Regents' Professor (Berkeley)
Reaction Engineering, Kinetics, Catalysis, Reactive Membranes, Microcontamination, Semiconductor Manufacturing

REYES SIERRA, Professor (Wageningen University)
Environmental Biotechnology, Semiconductor Manufacturing, Wastewater Treatment

SHANE A. SNYDER, Professor (Michigan State University)
Endocrine Disruptor and Emerging Contaminant Detection and Treatment, Water Reuse Technologies and Applications

ARMIN SOROOSHIAN, Assistant Professor (CalTech)
Aerosol Composition and Hygroscopicity, Climate Change

For further information

http://www.chee.arizona.edu

Chairman, Graduate Study Committee
Department of Chemical and Environmental Engineering
P.O. BOX 210011
The University of Arizona
Tucson, AZ 85721

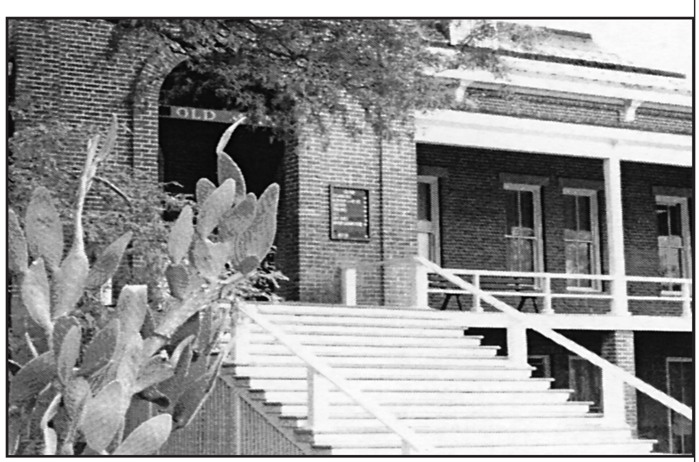
Chemical and Environmental Engineering at

THE UNIVERSITY OF ARIZONA

TUCSON ARIZONA

The Department of Chemical and Environmental Engineering at the University of Arizona offers a wide range of research opportunities in all major areas of chemical engineering and environmental engineering. Our department offers a comprehensive approach to sustainability which is grounded on the principles of conservation and responsible management of water, energy, and material resources. Research initiatives in solar and other renewable energy, desalinization, climate modeling, and sustainable nanotechnology are providing innovative solutions to the challenges of environmental sustainability. A significant portion of research effort is devoted to areas at the boundary between chemical and environmental engineering, including environmentally benign semiconductor manufacturing, environmental remediation, environmental biotechnology, and novel water treatment technologies.The department offers a fully accredited undergraduate degree in chemical engineering, as well as MS and PhD degrees in both chemical and environmental engineering. **Financial support is available through fellowships, government and industrial grants and contracts, teaching and research assistantships.**

Tucson has an excellent climate and many recreational opportunities. It is a growing modern city that retains much of the old Southwestern atmosphere.



Ira A. Fulton Schools of Engineering

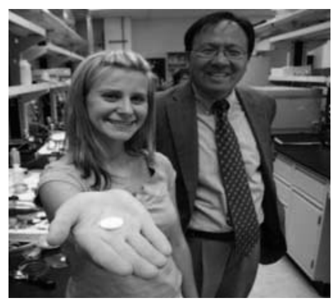
ARIZONA STATE UNIVERSITY

Chemical Engineering

Learn and discover in a multi-disciplinary research environment with opportunities in advanced materials, atmospheric chemistry, bioenergy, biotechnology, cancer therapeutics, electrochemistry and energy storage, electronic materials processing, engineering education, flexible displays, nanofluidics, process control, separation and purification technology, and soft materials.

Program Faculty

Jean M. Andino, Ph.D., P.E., Caltech.
Atmospheric chemistry, gas-phase kinetics and mechanisms, heterogeneous chemistry, air pollution control
James R. Beckman, Emeritus, Ph.D., Arizona.
Unit operations, applied mathematics, energy-efficient water purification, fractionation, CMP reclamation
Veronica A. Burrows, Ph.D., Princeton.
Engineering education, surface science, semiconductor processing, interfacial chemical and physical processes for sensors
Lenore Dai, Ph.D., Illinois.
Surface, interfacial, and colloidal science, nanorheology and microrheology, materials at the nanoscale, synthesis of novel polymer composites and "smart" materials
Jerry Y.S. Lin, Ph.D., Worcester Polytechnic Institute.
Advanced materials (inorganic membranes, adsorbents and catalysts) for applications in novel chemical separation and reaction processes
Mary Laura Lind, Ph.D., Caltech.
Advanced membrane materials for water purification, energy generation, and energy storage
David Nielsen, Ph.D., Queen's University at Kingston.
Biochemical engineering, metabolic engineering, bioreactor and bioprocess engineering, product recovery
Robert Pfeffer, Ph.D., New York University.
Dry particle coating and supercritical fluid processing to produce engineered particulates with tailored properties, fluidization, mixing, coating and processing of ultra-fine and nano-structured particulates, filtration of sub-micron particulates; agglomeration, sintering and granulation of fine particles
Jonathan D. Posner, Ph.D., California-Irvine.
Micro/nanofluidics, fuel cells, precision biology
Gregory B. Raupp, Ph.D., Wisconsin.
Gas-solid surface reactions, semiconductor materials processing, chemical vapor deposition (CVD), flexible electronics
Kaushal Rege, Ph.D., Rensselaer Polytechnic Institute.
Molecular and cellular engineering, engineered cancer therapeutics and diagnostics, cellular interactions in cancer metastasis
Daniel E. Rivera, Ph.D., Caltech.
Control systems engineering, dynamic modeling via system identification, optimized interventions for behavioral health, supply chain management
Michael R. Sierks, Ph.D., Iowa State.
Protein engineering, biomedical engineering, enzyme kinetics, antibody engineering
Cesar Torres, Ph.D., Arizona State.
Bioenergy, microbial electrochemical cells, microbial and biofilm kinetics, microscopic techniques to image biofilms
Bryan Vogt, Ph.D., Massachusetts.
Nanostructured materials for energy storage, organic electronics, supercritical fluids for materials processing, porous coatings for tissue engineering, nanomechanics of soft matter



Affiliate Faculty

Paul Johnson, Ph.D., Princeton.
Chemical migration and fate in the environment as applied to environmental risk assessment and the development, monitoring and optimization of technologies for aquifer restoration and water resources management
Bruce E. Rittmann, Ph.D., N.A.E., P.E., Stanford.
Environmental biotechnology, microbial ecology, environmental chemistry, environmental engineering

For additional details see
http://che.fulton.asu.edu/ or contact
Sharon Yee at (480) 965-8986 or
Sharon.Yee@asu.edu

***Vancouver** is the largest city in Western Canada, ranked the 1st most livable place in the world*. Vancouver's natural surroundings offer limitless opportunities for outdoor pursuits throughout the year - hiking, canoeing, mountain biking, skiing... In 2010, the city hosted the Olympic and Paraolympic Winter Games.*

Chemical and Biological Engineering Building, officially opened in 2006

Faculty

Muhannad Al-Darbi (Dalhousie)
Susan A. Baldwin (Toronto)
Xiaotao T. Bi (British Columbia)
Bruce D. Bowen (British Columbia)
Richard Branion (Saskatchewan)
Louise Creagh (California, Berkeley)
Sheldon J.B. Duff (McGill)
Naoko Ellis (British Columbia)
Peter Englezos (Calgary)
Norman Epstein (New York)
James Feng (Minnesota)
Bhushan Gopaluni (Alberta)
John R. Grace (Cambridge)
Christina Gyenge (British Columbia)
Elod Gyenge (British Columbia)
Savvas Hatzikiriakos (McGill)
Charles Haynes (California, Berkeley)
Dhanesh Kannangara (Ottawa)
Richard Kerekes (McGill)
Ezra Kwok (Alberta)
Anthony Lau (British Columbia)
Eric Legally (California, Santa Barbara)
C. Jim Lim (British Columbia)
Mark D. Martinez (British Columbia)
Madjid Mohseni (Toronto)
Colin Oloman (British Columbia)
Royann Petrell (Florida)
James M. Piret (MIT)
Dusko Posarac (Novi Sad)
Kevin J. Smith (McMaster)
Fariborz Taghipour (Toronto)
A. Paul Watkinson (British Columbia)

The University of British Columbia is the largest public university in Western Canada and is ranked among the top 40 institutes in the world by *Newsweek* magazine, the *Times Higher Education Supplement* and Shanghai Jiao Tong University.

Faculty of Applied Science

CHEMICAL AND BIOLOGICAL ENGINEERING

www.chbe.ubc.ca

MASTER OF APPLIED SCIENCE (M.A.SC.)
MASTER OF ENGINEERING (M.ENG.)
MASTER OF SCIENCE (M.SC.)
DOCTOR OF PHILOSOPHY (PH.D.).

Currently about 170 students are enrolled in graduate studies. The program dates back to the 1920s. Nowadays the department has a strong emphasis on interdisciplinary and joint programs, in particular with the Michael Smith Laboratories, Pulp and Paper Research Institute of Canada (PAPRICAN), Clean Energy Research Centre (CERC) and the BRIDGE program which links public health, engineering and policy research.

Main Areas of Research

Biological Engineering
Biochemical Engineering • Biomedical Engineering • Protein Engineering • Blood research • Stem Cells

Energy
Biomass and Biofuels • Bio-oil and Bio-diesel • Combustion, Gasification and Pyrolysis • Electrochemical Engineering • Fuel Cells • Hydrogen Production • Natural Gas Hydrates

Process Control

Pulp and Paper

Reaction Engineering

Environmental and Green Engineering
Emissions Control • Green Process Engineering • Life Cycle Analysis • Wastewater Treatment • Waste Management • Aquacultural Engineering

Particle Technology
Fluidization • Multiphase Flow • Fluid-Particle Systems • Particle Processing • Electrostatics

Kinetics and Catalysis

Polymer Rheology

Financial Aid

Students admitted to the graduate programs leading to the M.A.Sc., M.Sc. or Ph.D. degrees receive at least a minimum level of financial support regardless of citizenship (approx. $17,500/year for M.A.Sc and M.Sc and $19,000/year for Ph.D). Teaching assistantships are available (up to approx. $1,000 per year). All student are eligible for several Graduate Entrance Scholarships of $5,000/year and 4-year Doctoral Fellowships Scholarships of approx. $16,000/year.

**January 2010 survey, The Economist*

Mailing address: 2360 East Mall, Vancouver B.C., Canada V6T 1Z3 • gradsec@chbe.ubc.ca • tel. +1 (604) 822-3457

CHEMICAL AND BIOMOLECULAR ENGINEERING AT

UCLA

FOCUS AREAS

- ► Biomolecular and Cellular Engineering
- ► Process Systems Engineering (Simulation, Design, Optimization, Dynamics, and Control)
- ► Semiconductor Manufacturing and Electronic Materials

GENERAL THEMES

- ► Energy and the Environment
- ► Nanoengineering

FACULTY

J. P. Chang
(William F. Seyer Chair in Materials Electrochemistry)

P. D. Christofides

Y. Cohen

J. Davis
(Vice Provost Information Technology)

R.F. Hicks

L. Ignarro
(Nobel Laureate)

J. C. Liao
(Chancellor's Professor)

Y. Lu

V.I. Manousiouthakis

H.G. Monbouquette
(Dept. Chair)

G. Orkoulas

T. Segura

S.M. Senkan

Y. Tang

PROGRAMS

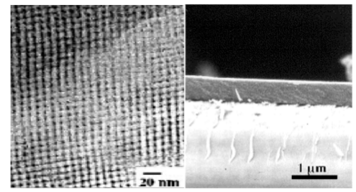
UCLA's Chemical and Biomolecular Engineering Department offers a program of teaching and research linking fundamental engineering science and industrial practice. Our Department has strong graduate research programs in Biomolecular Engineering, Energy and Environment, Semiconductor Manufacturing, Engineering of Materials, and Process and Control Systems Engineering.

Fellowships are available for outstanding applicants interested in Ph.D. degree programs. A fellowship includes a waiver of tuition and fees plus a stipend.

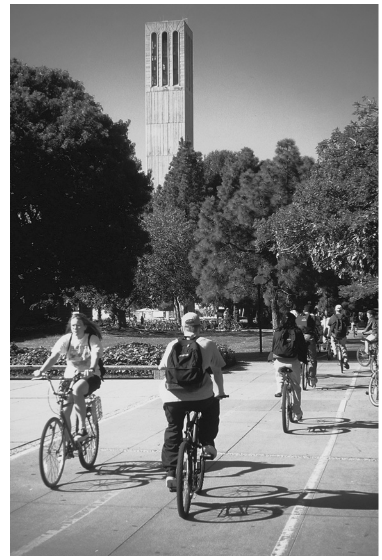
Located five miles from the Pacific Coast, UCLA's attractive 417-acre campus extends from Bel Air to Westwood Village. Students have access to the highly regarded engineering and science programs and to a variety of experiences in theatre, music, art, and sports on campus.

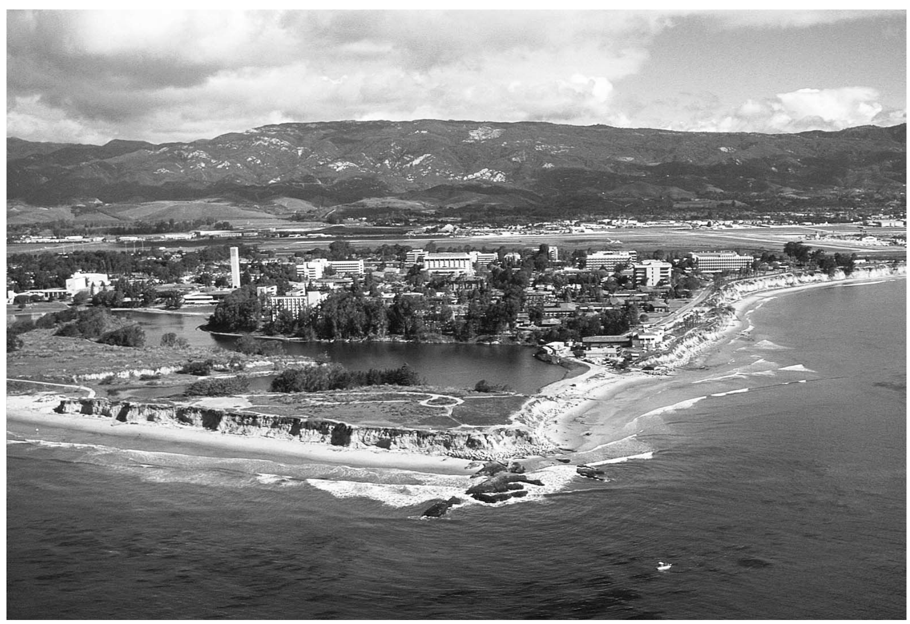
CONTACT

Admissions Office
Chemical and Biomolecular Engineering Department
5531 Boelter Hall • UCLA • Los Angeles, CA 90095-1592
Telephone at (310) 825-9063 or visit us at www.chemeng.ucla.edu



20 nm
1 µm





CALTECH
CHEMICAL ENGINEERING

"At the Leading Edge"

The Warren and Katharine Schlinger Laboratory for Chemistry and Chemical Engineering opened in March 2010

CALIFORNIA INSTITUTE OF TECHNOLOGY

Contact information:
Director of Graduate Studies
Chemical Engineering 210-41
California Institute of Technology
Pasadena, CA 91125

http://www.che.caltech.edu

Frances H. Arnold: Protein Engineering and Directed Evolution, Biocatalysis, Synthetic Biology, Biofuels

John F. Brady: Complex Fluids and Suspensions, Rheology, Transport Processes

Mark E. Davis: Biomedical Engineering, Catalysis, Advanced Materials

Richard C. Flagan: Aerosol Science, Atmospheric Chemistry and Physics, Bioaerosols, Nanotechnology, Nucleation

George R. Gavalas (emeritus)

Konstantinos P. Giapis: Plasma Processing, Ion-Surface Interactions, Nanotechnology

Sossina M. Haile: Advanced Materials, Fuel Cells, Energy, Electrochemistry, Catalysis and Electrocatalysis

Julia A. Kornfield: Polymer Dynamics, Crystallization of Polymers, Physical Aspects of the Design of Biomedical Polymers

John H. Seinfeld: Atmospheric Chemistry and Physics, Global Climate

David A. Tirrell: Macromolecular Chemistry, Biomaterials, Protein Engineering, Chemical Biology

Nicholas W. Tschoegl (emeritus)

Zhen-Gang Wang: Statistical Mechanics, Polymer Science, Biophysics

ADVANCE TO THE NEXT LEVEL
CHEMICAL ENGINEERING AT CARNEGIE MELLON
Unlock the next stage of your career. The graduate students and faculty at Carnegie Mellon are taking the field of Chemical Engineering to a new level. Power up with research in alternative energy, systems engineering, nanotechnology, bioengineering, and environmental engineering.
The game is just beginning. Take control of your future.
Carnegie Mellon
Department of Chemical Engineering
Pittsburgh, PA 15213-3890
PLAYER 1 SELECT
> Bioengineering
> Complex Fluids Engineering
> Energy Science and Engineering
> Envirochemical Engineering
> Process Systems Engineering
Graduate Degree Programs
> Doctorate
> Course Option Master
> Thesis Option Master
Department Home Page
www.cheme.cmu.edu
Online Graduate Application
www.cheme.edu/admissions
Contact Information
chegrad@andrew.cmu.edu
412.268.2230
START GAME

Case Western Reserve University

Advanced Research in Energy, Materials, and Bio-related applications

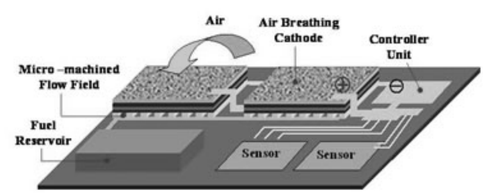
The graduate programs in Chemical Engineering at Case Western Reserve University prepare students for an independent, creative career in chemical engineering research in industry or academia. Research opportunities, especially in our core strengths of energy, advanced materials, and biological applications of chemical engineering, are many. You will find CWRU to be an exciting environment in which to carry out your graduate studies. Come help us invent the future.

Faculty

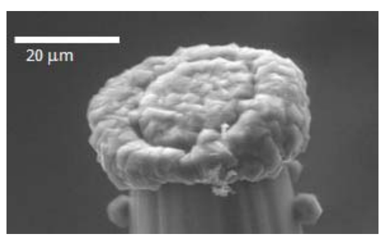
John C. Angus
Harihara Baskaran
Liming Dai
Donald L. Feke
Daniel J. Lacks
Uziel Landau
Chung-Chiun Liu
J. Adin Mann, Jr.
Heidi B. Martin
Syed Qutubuddin
R. Mohan Sankaran
Robert F. Savinell
Jesse Wainright

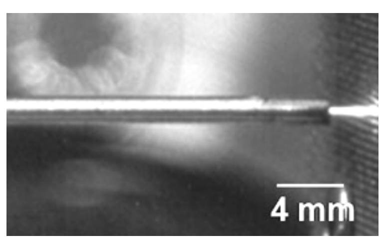
For more information on research opportunities, admission, and financial support:

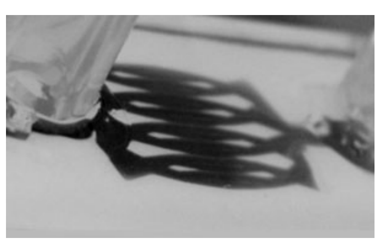
Graduate Coordinator
Department of Chemical Engineering
Case Western Reserve University
10900 Euclid Avenue
Cleveland, OH 44106-7217
chemeng@case.edu
http://www.case.edu/cse/eche



Microfabricated sensor-power system







Research Opportunities

Energy and Electrochemical Systems

Fuel Cells and Batteries
Electrochemical Engineering
Energy Storage
Membrane Transport, Fabrication

Advanced Materials and Devices

Synthetic Diamond
Coatings, Thin Films and Surfaces
Microsensors
Polymer Nanocomposites
Nanomaterials and Nanosynthesis
Particle Science and Processing
Molecular Simulations
Microplasmas and Microreactors

Biological Applications

Biomedical Sensors and Actuators
Neural Prosthetic Devices
Cell and Tissue Engineering
Transport in Biological Systems

CASE WESTERN RESERVE UNIVERSITY EST. 1826

Opportunities for Graduate Study in Chemical Engineering at the

UNIVERSITY OF CINCINNATI

M.S. and Ph.D. Degrees in Chemical Engineering

Faculty

A.P. Angelopoulos

Carlos Co

Junhang Dong

Joel Fried

Rakesh Govind

Vadim Guliants

Chia-chi Ho

Yuen-Koh Kao

Soon-Jai Khang

Joo-Youp Lee

Paul Phillips

Neville Pinto

Vesselin Shanov

Peter Smirniotis

Stephen W. Thiel

Financial Aid Available

The University of Cincinnati is committed to a policy of non-discrimination in awarding financial aid.

For Admission Information Contact

Barbara Carter
Graduate Studies Office
College of Engineering and Applied Science
Cincinnati, OH 45221-0077
513-556-5157
Barbara.carter@uc.edu
or
Professor Vadim Guliants
The Chemical Engineering Program
The School of Energy, Environmental, Biological and Medical Engineering
Cincinnati, Ohio 45221
vadim.guliants@uc.edu

Engineering Research Center that houses most chemical engineering research.

☐ **Emerging Energy Systems**
Catalytic conversion of fossil and renewable resources into alternative fuels, such as hydrogen, alcohols and liquid alkanes; solar energy conversion; inorganic membranes for hydrogen separation; fuel cells, hydrogen storage nanomaterials

☐ **Environmental Research**
Mercury and carbon dioxide capture from power plant waste streams, air separation for oxycombustion; wastewater treatment, removal of volatile organic vapors

☐ **Molecular Engineering**
Application of quantum chemistry and molecular simulation tools to problems in heterogeneous catalysis, (bio)molecular separations and transport of biological and drug molecules

☐ **Catalysis and Chemical Reaction Engineering**
Selective catalytic oxidation, environmental catalysis, zeolite catalysis, novel chemical reactors, modeling and design of chemical reactors, polymerization processes in interfaces, membrane reactors

☐ **Membrane and Separation Technologies**
Membrane synthesis and characterization, membrane gas separation, membrane filtration processes, pervaporation; biomedical, food and environmental applications of membranes; high-temperature membrane technology, natural gas processing by membranes; adsorption, chromatography, separation system synthesis, chemical reaction-based separation processes

☐ **Biotechnology**
Nano/microbiotechnology, novel bioseparation techniques, affinity separation, biodegradation of toxic wastes, controlled drug delivery, two-phase flow

☐ **Polymers**
Thermodynamics, polymer blends and composites, high-temperature polymers, hydrogels, polymer rheology, computational polymer science, molecular engineering and synthesis of surfactants, surfactants and interfacial phenomena

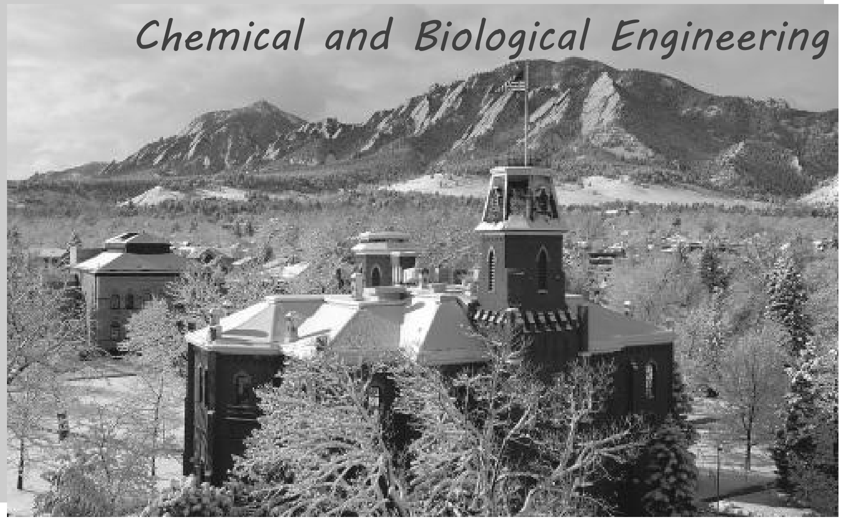
☐ **Bio-Applications of Membrane Science and Technology**
This IGERT program provides a unique educational opportunity for U.S. Ph.D. students in areas of engineering, science, medicine, or pharmacy with above focus. This program is supported by a five-year renewable grant from the National Science Foundation. The IGERT fellowship consists of an annual stipend of $30,000 for up to three years.

☐ **Institute for Nanoscale Science and Technology (INST)**
INST brings together three centers of excellence—the Center for Nanoscale Materials Science, the Center for BioMEMS and Nanobiosystems, and the Center for Nanophotonics—composed of faculty from the Colleges of Engineering, Arts and Sciences, and Medicine. The goals of the institute are to develop a world-class infrastructure of enabling technologies, to support advanced collaborative research on nanoscale phenomena.

University of Colorado at Boulder

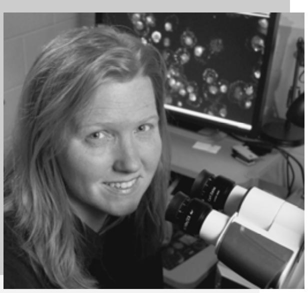
Why the University of Colorado?

- Diverse research thrusts and expertise
- Nationally recognized faculty in research and teaching
- Collegiality between faculty, staff, and students



Cutting Edge Research

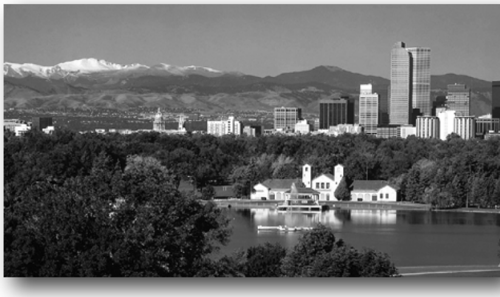
- **Biomaterials**: tissue engineering, biocompatible coatings, biosensors
  K.S. Anseth; C.N. Bowman; S.J. Bryant; J.L. Kaar; M.J. Mahoney; T.W. Randolph; D.K. Schwartz; J.W. Stansbury
- **Biopharmaceuticals**: delivery technologies and stable formulations for new drugs, metabolic engineering, drug delivery
  R.T. Gill; J.L. Kaar; D.S. Kompala; M.J. Mahoney; T.W. Randolph; D.K. Schwartz; J.W. Stansbury
- **Catalysis, Surface Science, and Thin Film Materials** : heterogeneous catalysis, catalysis for biomass conversion, zeolites, atomic and molecular layer deposition
  J.L. Falconer; S.M. George; J.W. Medlin; D.K. Schwartz; A.W. Weimer
- **Particle Technology and Complex Fluids**: fluid mechanics of suspensions, gas-particle fluidization, granular flow mechanics
  R.H. Davis; C.M. Hrenya; A. Jayaraman; A.W. Weimer
- **Computational Science**: classical and quantum simulations, statistical mechanics, continuum modeling
  C.M. Hrenya; A. Jayaraman; J.W. Medlin; C.B. Musgrave
- **Renewable Energy and Clean Energy Applications**: biofuels, solar energy, carbon capture, high-efficiency synthesis
  J.L. Falconer; S.M. George; R.T. Gill; C.M. Hrenya; A. Jayaraman; J.W. Medlin; C.B. Musgrave; R.D. Noble; A.W. Weimer
- **Membranes and Separations:** inorganic membranes, polymer membranes, ionic liquids
  R.H. Davis; J.L. Falconer; D.L. Gin; J.W. Medlin; R.D. Noble; D.K. Schwartz
- **Nanotechnology**: engineering materials at the nanoscale
  C.N. Bowman; S.M. George; D.L. Gin; A. Jayaraman; J.W. Medlin; D.K. Schwartz; M.P. Stoykovich; A.W. Weimer
- **Polymer Chemistry and Engineering**: chemical synthesis, applications of polymers and macromolecules
  K.S. Anseth; C.N. Bowman; S.J. Bryant; D.L. Gin; A. Jayaraman; J.W. Stansbury; M.P. Stoykovich



Professor Kristi Anseth, member of the National Academy of Engineering and National Institute of Medicine

Engineering Center, ECCH 111 · University of Colorado at Boulder · Boulder, CO 80309-0424
· Tel 303.492.7471 · Fax 303.492.4341 · www. Colorado.edu/che

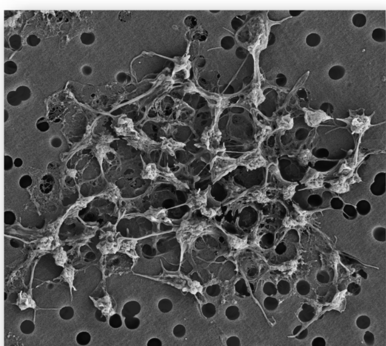
COLORADO SCHOOL OF MINES



Evolving from its origins as a school of mining founded in 1873, CSM is a unique, highly-focused University dedicated to scholarship and research in materials, energy, and the environment.

The Chemical Engineering Department at CSM maintains a high-quality, active, and well-funded graduate research program. Funding sources include federal agencies such as the NSF, DOE, DARPA, ONR, NREL, NIST, NIH as well as multiple industries. Research areas within the department include:

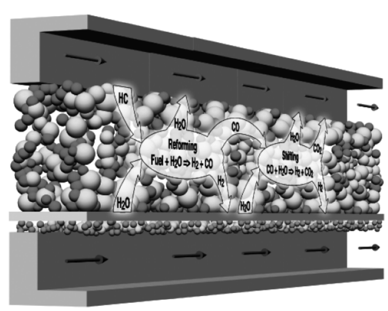
Material Science and Engineering
Organic and inorganic membranes (Way, Herring)
Polymeric materials (Dorgan, D.T. Wu, Liberatore)
Colloids and complex fluids (Marr, D.T. Wu, Liberatore, N. Wu)
Electronic materials (Wolden, Agarwal)
Molecular simulation and modeling (Ely, D.T. Wu, Sum, Maupin)



Biomedical and Biophysics Research
Microfluidics (Marr, Neeves)
Biological membranes (Sum)

Energy Research
Fuel cell catalysts and kinetics (Dean, Herring)
H_2 separation and fuel cell membranes (Way, Herring)
Natural gas hydrates (Sloan, Koh, Sum)
Biofuels: Biochemical and thermochemical routes (Liberatore, Herring, Dean, Maupin)

Finally, located at the foot of the Rocky Mountains and only 15 miles from downtown Denver, Golden, Colorado enjoys over 300 days of sunshine per year. These factors combine to provide year-round cultural, recreational, and entertainment opportunities virtually unmatched anywhere in the United States.



Faculty

- S. Agarwal (UCSB 2003)
- A.M. Dean (Harvard 1971)
- J.R. Dorgan (Berkeley 1991)
- J.F. Ely (Indiana 1971)
- A. Herring (Leeds 1989)
- C.A. Koh (Brunel 1990)
- M.W. Liberatore (Illinois 2003)
- D.W.M. Marr (Stanford 1993)
- C.M. Maupin (Utah 2008)
- R.L. Miller (CSM 1982)
- K.R. Neeves (Cornell 2006)
- E.D. Sloan (Clemson 1974)
- A.K. Sum (Delaware 2001)
- J.D. Way (Colorado 1986)
- C.A. Wolden (MIT 1995)
- D.T. Wu (Berkeley 1991)
- N. Wu (Princeton 2008)

http://chemeng.mines.edu

Colorado State University

Chemical & Biological Engineering

Research Areas

Bioanalytical Chemistry
Biofuels and Biorefining
Biomaterials
Cell and Tissue Engineering
Magnetic Resonance Imaging
Membrane Science
Microfluidics
Polymer Science
Synthetic and Systems Biology

Faculty

Travis S. Bailey, Ph.D., U. Minnesota
Laurence A. Belfiore, Ph.D., U. Wisconsin
David S. Dandy, Ph.D., Caltech
J.D. (Nick) Fisk, Ph.D., U. Wisconsin
Matt J. Kipper, Ph.D., Iowa State U.
James C. Linden, Ph.D., Iowa State U.
Christie Peebles, Ph.D., Rice U.
Ashok Prasad, Ph.D., Brandeis U.
Kenneth F. Reardon, Ph.D., Caltech
Brad Reisfeld, Ph.D., Northwestern U.
Qiang (David) Wang, Ph.D., U. Wisconsin
A. Ted Watson, Ph.D., Caltech
Ranil Wickramasinghe, Ph.D.,
U. Minnesota

View faculty and student research videos, find application information, and get other information at ***http://cbe.colostate.edu***

Research

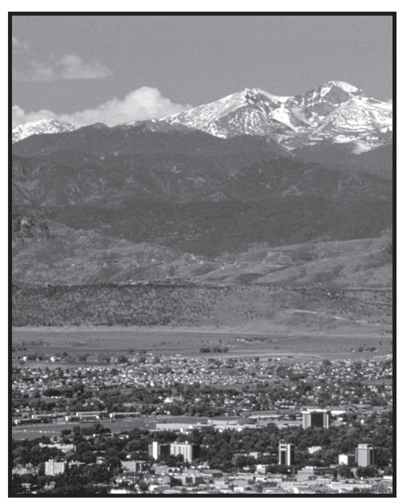
The graduate program in the Department of Chemical and Biological Engineering at Colorado State University offers students a broad range of cutting-edge research areas led by faculty who are world renowned experts in their respective fields. Opportunities for collaboration with many other department across the University are abundant, including departments in the Colleges of Engineering, Natural Sciences, and Veterinary Medicine and Biomedical Sciences.

Financial Support

Research Assistantships pay a competitive stipend. Students on assistantships also receive tuition support. The department has a number of research assistantships. Students select research projects in their area of interest from which a thesis or dissertation may be developed. Additional University fellowship awards are available to outstanding applicants.

Fort Collins

Located in Fort Collins, Colorado State University is perfectly positioned as a gateway to the Rocky Mountains. With its superb climate (over 300 days of sunshine per year), there are exceptional opportunities for outdoor pursuits including hiking, biking, skiing, and rafting.



For additional information or to schedule a visit of campus:

Department of Chemical and
Biological Engineering
Colorado State University
Fort Collins, CO 80523-1370
Phone: (970) 491-5253
Fax: (970) 491-7369
E-mail: cbe_grad@colostate.edu

GRADUATE STUDIES IN CHEMICAL AND BIOMOLECULAR ENGINEERING

UNIVERSITY *of* HOUSTON

Houston–
Dynamic Hub of Chemical and Biomolecular Engineering

Houston is at the center of the U.S. energy and chemical industries and is the home of NASA's Johnson Space Center and the world-renowned Texas Medical Center.

The University of Houston Department of Chemical and Biomolecular Engineering offers excellent facilities, competitive financial support, industrial internships and an environment conducive to personal and professional growth.

Houston offers an abundance of educational, cultural, business and entertainment opportunities. For a large and diverse city, Houston's cost of living is much lower than average.

Research Areas:

Advanced Materials
Alternative Energy
Biomolecular Engineering
Catalysis
Multi-Phase Flows
Nanotechnology
Plasma Processing
Reaction Engineering

Affiliated Research Centers:

Alliance for NanoHealth
http://www.nanohealthalliance.org/

Western Regional Center of Excellence for Biodefense and Emerging Infectious Diseases
http://rce.swmed.edu/rce6/theme_1.htm

National Large Scale Wind Turbine Testing Facility
http://www.thewindalliance.com

Texas Diesel Testing and Research Center
http://www.chee.uh.edu/dieselfacility/

UNIVERSITY OF HOUSTON
CULLEN COLLEGE OF ENGINEERING

For more information:

Visit: www.chee.uh.edu
Email: grad-che@uh.edu

Write: University of Houston
Chemical and Biomolecular Engineering
Graduate Admission
S222 Engineering Building 1
Houston, TX 77204-404

The University of Houston is an Equal Opportunity/Affirmative Action institution. Minorities, women, veterans and persons with disabilities are encouraged to apply.

UIC The University of Illinois at Chicago
Department of Chemical Engineering

MS and PhD Graduate Program

FACULTY

Sohail Murad, Professor and Head
Ph.D., Cornell University, 1979
E-Mail: Murad@uic.edu

Belinda S. Akpa, Assistant Professor
Ph. D., University of Cambridge, 2007
E-Mail: Akpa@uic.edu

John H. Kiefer, Professor Emeritus
Ph.D., Cornell University, 1961
E-Mail: Kiefer@uic.edu

Andreas A. Linninger, Associate Professor
Ph.D., Vienna University of Technology, 1992
E-Mail: Linninge@uic.edu

Ying Liu, Assistant Professor
Ph.D., Princeton University, 2007
E-mail: liuying@uic.edu

G. Ali Mansoori, Professor
Ph.D., University of Oklahoma, 1969
E-Mail: Mansoori@uic.edu

Randall Meyer, Assistant Professor
Ph.D., University of Texas at Austin, 2001
E-Mail: Rjm@uic.edu

Ludwig C. Nitsche, Associate Professor
Ph.D., Massachusetts Institute of Technology, 1989
E-Mail: LCN@uic.edu

John Regalbuto, Professor
Ph.D., University of Notre Dame, 1986
E-Mail: JRR@uic.edu

Christos Takoudis, Professor
Ph.D., University of Minnesota, 1982
E-Mail: Takoudis@uic.edu

Raffi M. Turian, Professor Emeritus
Ph.D., University of Wisconsin, 1964
E-Mail: Turian@uic.edu

Lewis E. Wedgewood, Associate Professor
Ph.D., University of Wisconsin, 1988
E-Mail: Wedge@uic.edu

Said Al-Hallaj, Adjunct Professor
Ph.D., IIllinois Institute of Technology, 2000
Email: sah@uic.edu

Cynthia J. Jameson, Professor Emeritus
Ph.D., University of Illinois at
Chicago-Urbana/Champagne, 1963
Email: cjjames@uic.edu

RESEARCH AREAS

Transport Phenomena: Transport properties of fluids, Slurry transport, Multiphase fluid flow. Fluid mechanics of polymers, Ferro fluids and other Viscoelastic media.

Thermodynamics: Molecular simulation and Statistical mechanics of liquid mixtures, Superficial fluid extraction/retrograde condensation, Asphaltene characterization, Membrane-based separations.

Kinetics and Reaction Engineering: Gas-solid reaction kinetics, Energy transfer processes, Laser diagnostics, and Combustion chemistry. Environmental technology, Surface chemistry, and optimization. Catalyst preparation and characterization, Supported metals, Chemical kinetics in automotive engine emissions. Density fuctional theory calculations of reaction mechanisms.

Biochemical Engineering: Bioinstrumentation, Bioseparations, Biodegradable polymers, Nonaqueous Enzymology, Optimization of mycobacterial fermentations.

Materials: Microelectronic materials and processing, Heteroepitaxy in group IV materials, and in situ surface spectroscopies at interfaces. Combustion synthesis of ceramics and synthesis in supercritical fluids, Magnetic resonance.

Product and Process: Development and design, Computer-aided modeling and simulation, Pollution prevention, Clean energy and clean water technologies with focus on Li-ion batteries, fuel cells, hydrogen, solar BIPV and water desalination.

Biomedical Engineering: Hydrodynamics of the human brain, Microvasculation, Fluid structure interaction in biological tissues, Targeted drug delivery and Medical imaging.

Nanoscience and Engineering: Molecular-based study of matter in nanoscale, Organic nanostructures, Self-assembly and Positional assembly. Properties of size-selected clusters.

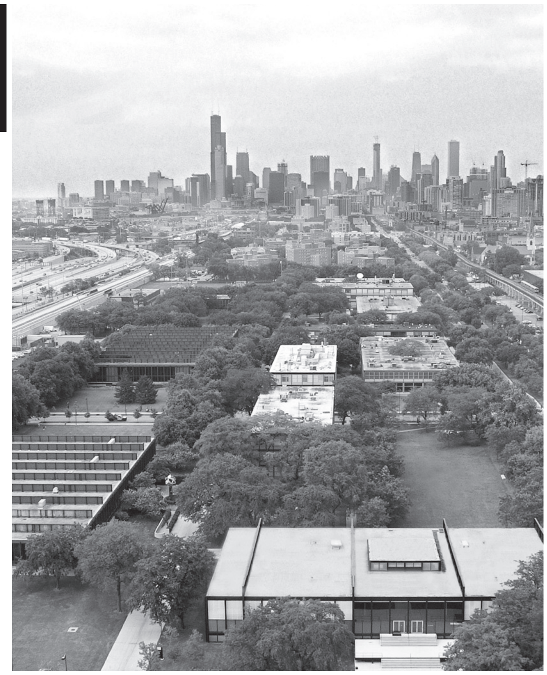
For more information, write to
Director of Graduate Studies • Department of Chemical Engineering
University of Illinois at Chicago • 810 S. Clinton St. • Chicago, IL 60607-7000 • (312) 996-3424 • Fax (312) 996-0808
URL: http://www.uic.edu/depts/chme/

Department of Chemical and Biological Engineering at Illinois Institute of Technology

The Department of Chemical and Biological Engineering (ChBE) at Illinois Institute of Technology (IIT) offers everything a student could want in a graduate program: internationally respected faculty, cutting-edge research centers, and collaborations with national laboratories, global companies, and other leading universities. Located just minutes from downtown Chicago, IIT gives students the best of both worlds—a thriving city known for its culture and social activities, and a prominent research university dedicated to solving the most complex challenges facing society.

In addition to the Ph.D. in chemical engineering, IIT's ChBE Department offers both thesis and non-thesis masters degrees in chemical, biological, and food process engineering. Within each degree program, students have the ability to concentrate their studies and research into a variety of disciplines, ranging from polymer engineering, fuel cell technology, and drug delivery to biosensors, renewable energy, and particle processing.

The department is actively and continuously committed to making positive and important contributions to society by providing the best possible education to all its students, and by offering the highest quality of scholarship through research activities at the forefront of scientific and technological knowledge. IIT is devoted to fostering the next generation of chemical and biological engineers, instilling in them a quest for innovation and a thirst for problem solving.



Faculty

Javad Abbasian
John L. Anderson
Hamid Arastoopour
Barry Bernstein
Donald J. Chmielewski
Ali Cinar
Dimitri Gidaspow
Nancy W. Karuri
Alex D. Nikolov
Satish J. Parulekar
Victor Perez-Luna
Jai Prakash
Vijay Ramani
Jay D. Schieber
J. Robert Selman
Fouad Teymour
David C. Venerus
Darsh T. Wasan

Research Areas

Biological Engineering • Energy and Sustainability • Complex Fluids • Systems Engineering • Fuel Cells and Batteries • Fluidization and Gasification • Hybrid Systems • Interfacial and Transport Phenomena • Nanotechnology Systems Engineering • Complex Systems • Advanced Process Control • Polymeric Materials Process Monitoring

ChBE at a Glance

- **IIT consistently ranks among the top 40 U.S. universities awarding engineering graduate degrees**
- **14 full-time faculty members, two of whom are National Academy of Engineering members and five of whom are AIChE fellows**
- **More than 150 graduate students enrolled in various programs**
- **Nearly $4.5 million in research funding per year**
- **Competitive stipends and fellowships available for highly motivated, well-qualified applicants**

www.chbe.iit.edu

10 W. 33rd Street, Room 127 Perlstein Hall • Chicago, IL 60616
chbe@iit.edu • 312.567.3040 (p) • 312.567.8874 (f)

ILLINOIS INSTITUTE OF TECHNOLOGY

Graduate program for M.S. and Ph.D. degrees in Chemical and Biochemical Engineering

FACULTY

Gary A. Aurand
North Carolina State U. 1996
Supercritical fluids/ High pressure biochemical reactors

Greg Carmichael
U. of Kentucky 1979
Global change/ Supercomputing/ Air pollution modeling

Jennifer Fiegel
Johns Hopkins 2004
Drug delivery/ Nano and microtechnology/ Aerosols

Vicki H. Grassian
U. of Calif.-Berkeley 1987
Surface science of environmental interfaces/ Heterogeneous atmospheric chemistry/Applications and implications of nanoscience and nanotechnology in environmental processes and human health

C. Allan Guymon
U. of Colorado 1997
Polymer reaction engineering/UV curable coatings/Polymer liquid crystal composites

Julie L.P. Jessop
Michigan State U. 1999
Polymers/ Microlithography/ Spectroscopy

David Murhammer
U. of Houston 1989
Insect cell culture/ Oxidative Stress/Baculovirus biopesticides

Eric E. Nuxoll
U. of Minnesota 2003
Controlled release/ microfabrication/ drug delivery

Tonya L. Peeples
Johns Hopkins 1994
Extremophile biocatalysis/Sustainable energy/ Green chemistry/ Bioremediation

David Rethwisch
U. of Wisconsin 1985
Membrane science/ Polymer science/ Catalysis

Aliasger K. Salem
U. of Nottingham 2002
Tissue engineering/ Drug delivery/Polymeric biomaterials/Immunocancer therapy/Nano and microtechnology

Alec B. Scranton
Purdue U. 1990
Photopolymerization/ Reversible emulsifiers/ Polymerization kinetics

Charles O. Stanier
Carnegie Mellon University 2003
Air pollution chemistry, measurement, and modeling/Aerosols

Venkiteswaran Subramanian
Indian Institute of Science 1978
Biocatalysis/Metabolism/ Gene expression/ Fermentation/Protein purification/Biotechnology

For information and application:

THE UNIVERSITY OF IOWA
Graduate Admissions
Chemical and Biochemical Engineering
4133 Seamans Center
Iowa City IA 52242-1527

1-800-553-IOWA
(1-800-553-4692)
chemeng@icaen.uiowa.edu
www.engineering.uiowa.edu/~chemeng/

Graduate Study in Chemical and Petroleum Engineering at the

UNIVERSITY OF KANSAS

The University of Kansas is the largest and most comprehensive university in Kansas. It has an enrollment of more than 28,000 and almost 2,000 faculty members. KU offers more than 100 bachelors', nearly 90 masters', and more than 50 doctoral programs. The main campus is in Lawrence, Kansas, with other campuses in Kansas City, Wichita, Topeka, and Overland Park, Kansas.

Graduate Programs

- M.S. degree with a thesis requirement in both chemical and petroleum engineering
- Ph.D. degree characterized by moderate and flexible course requirements and a strong research emphasis
- Typical completion times are 16-18 months for a M.S. degree and 4 1/2 years for a Ph.D. degree (from B.S.)

Faculty

Cory Berkland *(Ph.D., Illinois)*
Kyle V. Camarda *(Ph.D., Illinois)*
R.V. Chaudhari *(Ph.D., Bombay University)*
Michael Detamore *(Ph.D., Rice)*
Prajna Dhar *(Ph.D., Florida State)*
Stevin H. Gehrke *(Ph.D., Minnesota)*
Don W. Green, *(Ph.D., Oklahoma)*
Jenn-Tai Liang *(Ph.D., Texas)*
Trung V. Nguyen *(Ph.D., Texas A&M)*
Karen J. Nordheden *(Ph.D., Illinois)*
Russell D. Ostermann *(Ph.D., Kansas)*
Aaron Scurto *(Ph.D., Notre Dame)*
Marylee Z. Southard *(Ph.D., Kansas)*
Susan M. Williams *(Ph.D., Oklahoma)*
Bala Subramaniam *(Ph.D., Notre Dame)*
Shapour Vossoughi *(Ph.D., Alberta, Canada)*
Laurence Weatherley, Chair *(Ph.D., Cambridge)*
G. Paul Willhite *(Ph.D., Northwestern)*

Research

Biofuels and Biorefining
Catalytic Kinetics and Reaction Engineering
Catalytic Materials and Membrane Processing
Controlled Drug Delivery
Corrosion, Fuel Cells, Batteries
Electrochemical Reactors and Processes
Electronic Materials Processing
Enhanced Oil Recovery Processes
Fluid Phase Equilibria and Process Design
Liquid/Liquid Systems
Molecular Product Design
NanoTechnology for Biological Applications
Process Control and Optimization
Protein and Tissue Engineering
Supercritical Fluid Applications
Waste Water Treatment

Financial Aid

Financial aid is available in the form of research and teaching assistantships and fellowships/scholarships. A special program is described below.

Madison & Lila Self Graduate Fellowship

For additional information and application:
http://www2.ku.edu/~selfpro/

Research Centers

Tertiary Oil Recovery Program (TORP)
30 years of excellence in enhanced oil recovery research
http://www.torp.ku.edu

Center for Environmentally Beneficial Catalysis (CEBC)
NSF Engineering Research Center
https://rhodium.cebc.ku.edu

Transportation Research Institute (TRI)
http://www.kutri.ku.edu

Contacts

Website for information and application:

http://www.cpe.engr.ku.edu/

Graduate Program
Chemical and Petroleum Engineering
University of Kansas—Learned Hall
1530 W. 15th Street, Room 4132
Lawrence, KS 66045-7609

phone: 785-864-2900
fax: 785-864-4967
e-mail: **cpegrad@ku.edu**

LOUISIANA STATE UNIVERSITY

Cain Department of Chemical Engineering

THE CITY

Baton Rouge is the state capital and home of the state's flagship institution, LSU. Situated near the Acadian region, Baton Rouge blends the Old South and Cajun cultures. Baton Rouge is one of the nation's busiest ports and the city's economy rests heavily on the chemical, oil, plastics, and agricultural industries. The great outdoors provide excellent year-round recreational activities, especially fishing, hunting, and water sports. The proximity of New Orleans provides for superb nightlife, especially during Mardi Gras. The city is also only two hours away from the Mississippi Gulf Coast, and four hours from either Gulf Shores or Houston.

THE DEPARTMENT

- MS (thesis and non-thesis) and PhD Programs
- Approximately 50 graduate students
- Average research funding more than $2 million per year
- Access to outstanding experimental facilities including CAMD (the LSU Synchrotron) and the Polymer Analysis Facility (PAL)
- Access to outstanding computational facilities including four LSU supercomputers (over 18.47 TFlops), over 250 TB high-performance storage, LONI and National LambdaRail connectivity, and state-of-the-art graphics and visualization centers.

FINANCIAL AID

Assistantships at $17,500 - $29,600, with full tuition waiver, waiver of non-resident fees, and health insurance benefits.

TO APPLY, CONTACT

GRADUATE COORDINATOR
Cain Department of Chemical Engineering
Louisiana State University
Baton Rouge, Louisiana 70803
Telephone: 1-800-256-2084 FAX: 225-578-1476
e-mail: gradcoor@lsu.edu

LSU IS AN EQUAL OPPORTUNITY/ACCESS UNIVERSITY

FACULTY

M.G. BENTON
Cain Professor/Asst. Professor; PhD, University of Wisconsin
Genomics, Bioengineering, Metabolic Engineering, Biosensors

K.M. DOOLEY
BASF Professor; PhD, University of Delaware
Heterogeneous Catalysis, High-Pressure Separations

J.C. FLAKE
Cain Professor/Assc. Professor; PhD, Georgia Institute of Technology
Semiconductor Processing, Microelectronic Device Fabrication

G.L. GRIFFIN
Nusloch Professor; PhD, Princeton University
Electronic Materials, Surface Chemistry, CVD

J.E. HENRY
Cain Professor/Asst. Professor; PhD, Texas A&M University
Biochemical Engineering, Biomimetic Materials, Biosensors

M.A. HJORTSØ
Nusloch Professor; PhD, University of Houston
Biochemical Reaction Engineering, Applied Math

F.R. HUNG
Cain Professor/Asst. Professor; PhD, North Carolina State University
Nanoporous Materials, Confined Fluids, Liquid Crystals

F.C. KNOPF
Anding Professor; PhD, Purdue University
Supercritical Fluid Extraction, Ultrafast Kinetics

K. NANDAKUMAR
Cain Chair Professor; PhD, Princeton University
Computational Fluid Dynamics and Modeling of Multiphase Flows

R.W. PIKE
Horton Professor; PhD, Georgia Institute of Technology
Fluid Dynamics, Reaction Engineering, Optimization

J.A. ROMAGNOLI
Cain Chair Professor; PhD, University of Minnesota
Process Control

J.J. SPIVEY
Shivers Professor; PhD, Louisiana State University
Catalysis

L.J. THIBODEAUX
Coates Professor; PhD, Louisiana State University
Chemodynamics, Hazardous Waste Transport

K.E. THOMPSON
Lowe Professor/Assc. Professor; PhD, University of Michigan
Transport and Reaction in Porous Media

K.T. VALSARAJ
Roddy Distinguished Professor; PhD, Vanderbilt University
Environmental Transport, Separations

D.M. WETZEL
Haydel Professor/Assc. Professor; PhD, University of Delaware
Hazardous Waste Treatment, Drying

M.J. WORNAT
Harvey Professor; PhD, Massachusetts Institute of Technology
Combustion, Heterogeneous Reactions

University of Maine

Department of Chemical and Biological Engineering

The University - The campus is situated near the Penobscot and Stillwater Rivers in the town of Orono, Maine. The campus is large enough to offer various activities and events and yet is small enough to allow for one-on-one learning with faculty. The University of Maine is known for its hockey team, but also has a number of other sports activities. Not far from campus is the Maine Coast and Acadia National Park. North and west are alpine and cross-country ski resorts, Baxter State Park, and the Allagash Water Wilderness area.

DOUGLAS BOUSFIELD PhD (UC Berkeley)
Fluid mechanics, printing, coating processes, micro-scale modeling

ALBERT CO PhD (Wisconsin)
Polymeric fluid dynamics, rheology, transport phenomena, numerical methods

WILLIAM DESISTO PhD (Brown)
Advance materials, thin film synthesis, porous thin film filters for chem./bio sensors

DARRELL DONAHUE PhD (North Carolina State)
Biosensors in food and medical applications, risk assessment modeling, statistical process control

JOSEPH GENCO PhD (Ohio State)
Oxygen delignification, refining, pulping, pulp bleaching

JOHN HWALEK PhD (Illinois)
Process information systems, heat transfer

MICHAEL MASON PhD (UC Santa Barbara)
Laser scanning confocal microscopy, time-resolved imaging of molecular nanoprobes for biological systems

PAUL MILLARD PhD (Maryland)
Microbial biosensors, physiological genomics, fluorescence technology

DAVID NEIVANDT PhD (Melbourne)
Conformation of interfacial species, surface spectroscopies/microscopies

HEMANT PENDSE PhD (Syracuse) *Chair*
Sensor development, colloid systems, particulate and multiphase processes

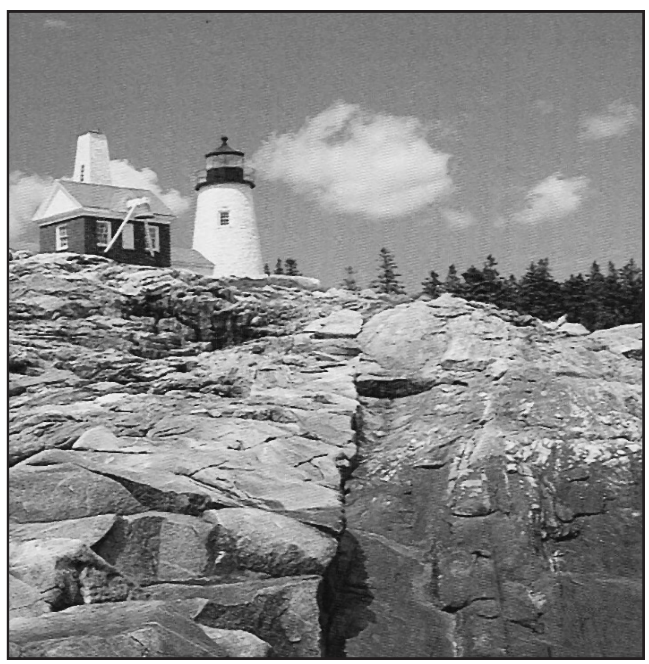
DOUGLAS RUTHVEN PhD ScD (Cambridge)
Fundamentals of adsorption and processes

ADRIAAN VAN HEININGEN PhD (McGill)
Pulp and paper manufacture and production of biomaterials and biofuels

G. PETER VAN WALSUM PhD (Dartmouth)
Renewable energy, fuels and chemicals, bioprocessing, process engineering

M. CLAYTON WHEELER PhD (Texas-Austin)
Chemical sensors, fundamental catalysis, surface science

The department has a long history of interactions with industry. Research projects often come from actual industrial situations. Various research programs, such as the Paper Surface Science Program, have industrial advisory boards that give students key contacts with industry. We have formed an alliance with the Institute of Molecular Biophysics (IMB) that brings to us partnerships with The Jackson Laboratory (TJL) and Maine Medical Center Research Institute (MMCRI). New research directions in the area of forest biorefinery, biosensors, and molecular biophysics give students opportunities to do research at the interface between engineering and the biological sciences.



For information about the graduate program:
Graduate Coordinator,
Department of Chemical and Biological Engineering
University of Maine, Orono, ME 04469
call 207 581-2277 • e-mail gradinfo@umche.maine.edu *or* bousfld@maine.edu • visit www.umche.maine.edu

University of Massachusetts - Amherst

EXPERIENCE OUR PROGRAM IN CHEMICAL ENGINEERING

Amherst is a beautiful New England college town in Western Massachusetts. Set amid farmland and rolling hills, the area offers pleasant living conditions and extensive recreational facilities, and urban pleasures are easily accessible.

For application forms and further information on fellowships and assistantships, academic and research programs, and student housing, see:
http://www.ecs.umass.edu/~chemeng
or contact:
Graduate Program Director
Department of Chemical Engineering
159 Goessmann Lab., 686 N. Pleasant St.
University of Massachusetts
Amherst, MA 01003-9303
Email: chegradprog@ecs.umass.edu

Facilities:
Instructional, research, and administrative facilities are housed in close proximity to each other. In addition to space in Goessmann Lab., including the ChE Alumni Classroom used for teaching and research seminars, we have laboratories in the Conte National Center for Polymer Research. In 2004 we dedicated the $25-million facilities of Engineering Lab II (ELab II), which includes 57,000-sq. ft of state-of-the-art laboratory facilities and office space.

FACULTY:

Surita R. Bhatia (*Princeton*)
W. Curtis Conner, Jr. (*Johns Hopkins*)
Paul J. Dauenhauer (*University of Minnesota*)
Jeffrey M. Davis (*Princeton*)
Wei Fan *(University of Tokyo)*
Neil S. Forbes (*University of California, Berkeley*)
David M. Ford (*University of Pennsylvania*)
Michael A. Henson (*Univ. of California, Santa Barbara*)
George W. Huber (*University of Wisconsin, Madison*)
Michael F. Malone (*University of Massachusetts, Amherst*)
Dimitrios Maroudas (*MIT*)
Peter A. Monson (*University of London*)
T. J. (Lakis) Mountziaris, Department Head (*Princeton*)
Shelly R. Peyton *(University of California, Irvine)*
Constantine Pozrikidis (*University of Illinois, Urbana-Champaign*)
Susan C. Roberts (*Cornell*)
Lianhong Sun (*Caltech*)
H. Henning Winter (*University of Stuttgart*)

Current areas of Ph.D. research in the Department of Chemical Engineering receive support at a level of over $4 million per year through external research grants. Examples of research areas include, but are not limited to, the following.

- **Bioengineering:** cellular engineering; metabolic engineering ; targeted bacteriolytic cancer therapy; assembly of biochemical pathways for synthesis of small molecules; systems biology; genetic circuit design...
- **Biofuels and Sustainable Energy:** catalysis, catalytic fast pyrolysis of biomass; catalytic microwave engineering; fuel cells; energy engineering…
- **Fluid Mechanics and Transport Phenomena:** biofluid dynamics and blood flow; hydrodynamics of microencapsulation; mechanics of cells, capsules, and suspensions; modeling microscale flows and transport phenomena; hydrodynamic stability and pattern formation; interfacial flows; gas-particle flows…
- **Materials Science and Engineering:** design and characterization of new catalytic materials; thin film and nanostructured materials for microelectronics and photonics; colloids and biomaterials; rheology and phase behavior of associative polymer solutions; polymeric materials processing...
- **Molecular and Multi-scale Modeling & Simulation:** computational quantum chemistry and kinetics; molecular modeling for nanotechnology; molecular-level behavior of fluids confined in porous materials; molecular-to-reactor scale modeling of transport and reaction processes in materials synthesis; atomistic-to-continuum scale modeling of thin films and nanostructured materials; systems-level analysis using deterministic and stochastic atomic-scale simulators; modeling and control of biochemical reactors; nonlinear process control theory ...

McGill Chemical Engineering

The department offers M. Eng. and PhD degrees with funding available and top-ups for those who already have funding.

Downtown Montreal, Canada

Montreal is a multilingual metropolis with a population over three million. Often called the world's second-largest French-speaking city, Montreal also boasts an English-speaking population of over 400,000. McGill itself is an English-language university, though it offers you countless opportunities to explore the French language.

McGill's Arts Building

For more information and graduate program applications:
***Visit*: www.mcgill.ca/chemeng/**
***Write*:**
Department of Chemical Engineering
McGill University
3610 University St
Montreal, QC H3A 2B2 CANADA
***Phone*: (514) 398-4494**
***Fax*: (514) 398-6678**
***E-mail*: inquire.chegrad@mcgill.ca**

D. BERK, Department Chair (Calgary)
Biological and chemical treatment of wastes, crystallization of fine powders, reaction engineering [dimitrios.berk@mcgill.ca]

D. G. COOPER, (Toronto)
Prod. of bacteriophages & biopharmaceuticals, self-cycling ferment., bioconversion of xenobiotics [david.cooper@mcgill.ca]

S. COULOMBE, Canada Research Chair (McGill)
Plasma processing, nanofluids, transport phenomena, optical diagnostic and process control [sylvain.coulombe@mcgill.ca]

J. M. DEALY, Emeritus Professor (Michigan)
Polymer rheology, plastics processing [john.dealy@mcgill.ca]

J.T. GOSTICK, (Waterloo)
Electrochemical energy storage and conversion, porous materials characterization, multiphase transport phenomena [jeff.gostick@mcgill.ca]

R. J. HILL, Canada Research Chair (Cornell)
Fuzzy colloids, biomimetic interfaces, hydrogels, and nanocomposite membranes [reghan.hill@mcgill.ca]

E. A. V. JONES, (CalTech) Canada Research Chair
Biofluid dynamics, biomechanics, tissue engineering, developmental biology & microscopy [liz.jones@mcgill.ca]

M. R. KAMAL, Emeritus Professor (Carnegie-Mellon)
Polymer proc., charac., and recycling [musa.kamal@mcgill.ca]

A.-M. KIETZIG, (British Columbia)
Functional surface engineering, material processing with lasers, interfacial phenomena [anne.kietzig@mcgill.ca]

R. LEASK, William Dawson Scholar (Toronto)
Biomedical engineering, fluid dynamics, cardiovascular mechanics, pathobiology [richard.leask@mcgill.ca]

M. MARIC, (Minnesota)
Block copolymers for nano-porous media, organic electronics, controlled release; "green" plasticisers [milan.maric@mcgill.ca]

J.- L. MEUNIER, (INRS-Energie, Varennes)
Plasma science & technology, deposition techniques for surface modifications, nanomaterials [jean-luc.meunier@mcgill.ca]

R. J. MUNZ, (McGill)
Thermal plasma tech, torch and reactor design, nanostructured material synthesis, environmental apps [richard.munz@mcgill.ca]

S. OMANOVIC, (Zagreb)
Biomaterials, protein/material interactions, bio/immunosensors, (bio)electrochemistry [sasha.omanovic@mcgill.ca]

T. M. QUINN, (MIT) Canada Research Chair
Soft tissue biophysics, mechanobiology, biomedical engineering, adherent cell culture technologies [thomas.quinn@mcgill.ca]

A. D. REY, James McGill Professor (California-Berkeley)
Computational material sci., thermodynamics of soft matter and complex fluids, interfacial sci. and eng. [alejandro.rey@mcgill.ca]

P. SERVIO, Canada Research Chair (British Columbia)
High-pressure phase equilibrium, crystallization, polymer coatings [phillip.servio@mcgill.ca]

N. TUFENKJI, Canada Research Chair (Yale)
Environmental and biomedical eng., bioadhesion and biosensors, bio- and nano- technologies [nathalie.tufenkji@mcgill.ca]

V. YARGEAU, (Sherbrooke)
Environmental control of pharmaceuticals, biodegradation of contaminants in water, biohydrogen [viviane.yargeau@mcgill.ca]

Graduate Studies in Chemical Engineering

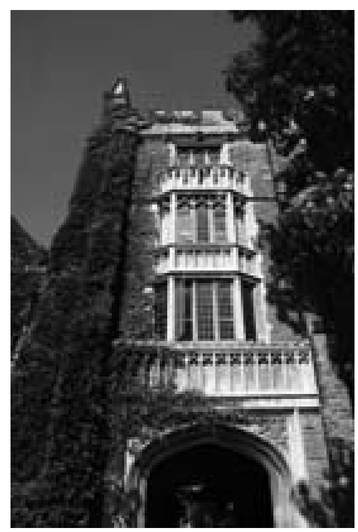
McMaster University ENGINEERING

We offer a Ph. D. program and three Master's options (Thesis, Project, Internship) in the following research areas:

- **Biomaterials:** Tissue engineering, biomedical engineering, blood-material interactions
  J.L. Brash, K. Jones, H. Sheardown,
- **Bioprocessing:** Bioseparation, environmental engineering,
  C. Filipe, T. Hoare, R. Ghosh,
- **Membranes:** Fabrication, characterization, and transport phenomena
  J. Dickson, C. Filipe, R. Ghosh
- **Polymer Science:** Interfacial engineering, polymerization, polymer characterization, synthesis
  T. Hoare, R. H. Pelton, S. Zhu, K. Kostanski (Adjunct)
- **Polymer Engineering:** Polymer processing, rheology, computer modelling, extrusion
  A. N. Hrymak, M. Thompson, J. Vlachopoulos, S. Zhu
- **Process Systems Engineering:** Multivariate statistical methods, computer process control, optimization
  B. Chachuat, J. F. MacGregor, V. Mahalec, T. E. Marlin, P. Mhaskar, C. L. E. Swartz,

We will provide financial support to any successful applicant who does not already have external support. In addition we have a limited number of teaching and research assistantships.

Why choose McMaster?



Hamilton is a city of over 500,000 situated in Southern Ontario. We are located about 100 km from both Niagara Falls and Toronto. McMaster University is one of Canada's top 8 research intensive universities. An important aspect of our research effort is the extent of the interaction between faculty members both within the department itself and with other departments at McMaster. Faculty are engaged in leading edge research and we have concentrated research groups that collaborate with international industrial sponsors:

- Centre for Pulp and Paper Research
- Centre for Advanced Polymer Processing & Design (CAPPA-D)
- McMaster Institute of Polymer Production Technology (MIPPT)
- McMaster Advanced Control Consortium (MACC)

FOR ON-LINE APPLICATION FORMS AND INFORMATION PLEASE CONTACT

Graduate Secretary
Department of Chemical Engineering
McMaster University
Hamilton, ON L8S 4L7
CANADA

Phone: 905-525-9140 X 24292
Fax: 905-521-1350
Email: chemeng@mcmaster.ca
http://www.chemeng.mcmaster.ca


MichiganEngineering
Experience the MICHIGAN Difference
Michigan is a world-class university with top-ranked programs.
Ann Arbor is one of the best places to live in the country.
Outstanding Faculty
· 25 faculty with diverse research topics
· 3 National Academy of Engineering members
· 10 faculty with national awards for research and teaching
· 6 textbooks/monographs by our faculty
Our Program
· 100 graduate students
· Teaching fellow program
· Professional development/networking at national conferences
UNIVERSITY OF MICHIGAN
Department of Chemical Engineering
The University of Michigan
3074 H.H. Dow
Ann Arbor, MI 48109
(734) 763-1148
che.engin.umich.edu
che-gradquestions@umich.edu

UNIVERSITY OF MINNESOTA

Driven to Discover℠

Leadership and Innovation in Chemical Engineering and Materials Science

Research Areas
- *Biotechnology and Bioengineering*
- *Ceramics and Metals*
- *Coating Processes and Interfacial Engineering*
- *Crystal Growth and Design*
- *Electronic, Photonic and Magnetic Materials*
- *Energy*
- *Fluid Mechanics*
- *Polymers*
- *Reaction Engineering and Chemical Process Synthesis*
- *Theory and Computation*

The Crucible, outside of Amundson Hall
Photo Credit: Patrick O'Leary

The Department of Chemical Engineering and Materials Science at the University of Minnesota-Twin Cities has been renowned for its pioneering scholarly work and for its influence in graduate education for the past half-century. Our department has produced numerous legendary engineering scholars and current leaders in both academia and industry. With its pacesetting research and education program in chemical engineering encompassing reaction engineering, multiphase flow, statistical mechanics, polymer science and bioengineering, our department was the first to foster a far-reaching marriage of the Chemical Engineering and Materials Science programs into an integrated department.

For the past few decades, the chemical engineering program has been consistently ranked as the top graduate program in the country by the National Research Council and other ranking surveys. The department has been thriving on its ability to foster interdisciplinary efforts in research and education; most, if not all of our active faculty members are engaged in intra- or interdepartmental research projects. The extensive collaboration among faculty members in research and education and the high level of co-advising of graduate students and research fellows serves to cross-fertilize new ideas and stimulate innovation. Our education and training are known not only for rigorously delving into specific and in-depth subjects, but also for their breadth and global perspectives. The widely ranging collection of high-impact research projects in these world-renowned laboratories provides students with a unique experience, preparing them for careers that are both exciting and rewarding.

Downtown Minneapolis as seen from campus
Photo Credit; Patrick O'Leary

Faculty:

Eray Aydil
Frank S. Bates
Aditya Bhan
Matteo Cococcioni
Edward L. Cussler
Prodromos Daoutidis
Jeffrey J. Derby
Kevin Dorfman
Lorraine F. Francis
C. Daniel Frisbie
William W. Gerberich
Russell J. Holmes
Wei-Shou Hu
Yiannis Kaznessis
Efrosini Kokkoli
Satish Kumar
Chris Leighton
Timothy P. Lodge
Christopher W. Macosko
Alon V. McCormick
K. Andre Mkhoyan
David C. Morse
Lanny D. Schmidt
David A. Shores
William H. Smyrl
Friedrich Srienc
Robert T. Tranquillo
Michael Tsapatsis
Renata Wentzcovitch
Kechun Zhang

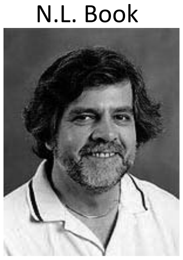
For more information contact:

Julie Prince, Program Associate
612-625-0382
princ004@umn.edu
URL: http://www.cems.umn.edu

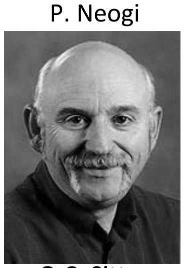
Downtown Saint Paul
Photo Credit: Patrick O'Leary


M.H. Al-Dahhan A.I. Liapis


N.L. Book D.K. Ludlow




D. Forciniti P. Neogi

D.B. Henthorn O.C. Sitton


K.H. Henthorn J.-C. Wang


S. Lee Y. Xing

MISSOURI S&T University of Science & Technology

Graduate Studies at Chemical and Biological Engineering

Faculty Research Interests: Adsorbents • Adsorption Phenomena • Aerosols • Alternative Fuels • Amyloidosis • Bacterial • Respiration • Bioengineering • Biomaterials • Biomimetics • Bioseparations • Brownian dynamics • Chem/Bio Counterterrorism • Chromatography • Computational Fluid Dynamics • Controlled release • Drug delivery • Electrocatalysis • Electrochemical deposition • Electro-osmosis • Engineering Design • Enhanced oil recovery • Environmental Engineering • Fermentation • Flow in micro channels • Fractals • Fuel cells • Hydrodynamics • Hydrogen technology • Information Systems • Interfacial phenomena • Light scattering • Lyophilization • Membranes • Mixing • Molecular biology • Molecular dynamics • Molecular microbiology • Nanomaterials • Nanotubes • Neutron reflectivity • Neutron scattering • Particle science and Technology • Peptide synthesis • Photochemical reactions • Photochemical reactors • Polymer Processing • Polymerization • Polymers • Radiation tomography • Reactions in supercritical systems • Reactor analysis • Reactor engineering • Self-Assembly • Sensors • Separations in a chip • Sonochemistry • Stability analysis • Statistical mechanics • Stepped Surfaces • Supercritical fluids • Surface analysis • Thin liquid films • Tribology • Turbulence • Wetting

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

Chemical and Biological Engineering
Graduate Studies
143 Schrenk Hall
400 W. 11th Street
Rolla, MO 65409-1230

Web: chemeng.mst.edu
Email: mstchemengr@mst.edu

THE FACES OF THE CHEMICAL ENGINEERS IN THE 21ST CENTURY

The University of New Mexico

We are the future of chemical engineering! Chemical engineers in the 21st century are challenged with rapidly developing technologies and exciting new opportunities. Pursue your graduate degree at UNM in a stimulating, student-centered, intellectual environment, brought together by forward-looking research. We offer full tuition, health care and competitive stipends.

The ChE faculty are leaders in exploring phenomena on the meso-, micro-, and nanoscales. We offer graduate research projects in biotechnology, biomaterials and biomedical engineering, catalysis and interfacial phenomena; microengineered materials and self-assembled nanostructures; plasma processing and semiconductor fabrication; polymer theory and modeling.

The department enjoys extensive interactions and collaborations with New Mexico's federal laboratories: Los Alamos National Laboratory, Sandia National Laboratories, and the Air Force Research Laboratory, as well as high technology industries both locally and nationally.

Albuquerque is a unique combination of old and new, the natural world and the manmade environment, the frontier town and the cosmopolitan city, a harmonious blend of diverse cultures and peoples.

Faculty	Research Areas
Plamen Atanassov	• Electroanalytical Chemistry, Biomedical Engineering
C. Jeffrey Brinker	• Ceramics, Sol-Gel Processing, Self-assembled Nanostructures
Heather Canavan	• Stimulus-responsive materials, cell/surface interactions, Biomedical Engineering
Joseph L. Cecchi	• Semiconductor Manufacturing Technology, Plasma Etching and Deposition
Eva Chi	• Protein interfacial dynamics, protein aggregation, protein misfolding diseases
John G. Curro	• Polymer Theory, Computational Modeling
Abhaya K. Datye	• Catalysis, Interfaces, Advanced Materials
Elizabeth L. Dirk	• Biomaterials, Tissue Engineering
Julia E. Fulghum	• Surface Characterization, 3-D Materials Characterization
Steven Graves	• Biomolecular Assemblies, Protease Mechanisms, Flow Cytometry
Sang M. Han	• Semiconductor Manufacturing Technology, Plasma Etching and Deposition
Ronald E. Loehman	• Glass-Metal and Ceramic-Metal Bonding and Interfacial Reactions
Dimiter Petsev	• Complex fluids, Nanoscience, Electrokinetic phenomena
Timothy L. Ward	• Aerosol Materials Synthesis, Inorganic Membranes
David G. Whitten	• Biosensors, Conjugated polymer photophysics and bioactivity in films and interfacial assemblies, Multicomponent systems and their applications

For more information, contact:

Sang Han, Graduate Advisor
Chemical and Nuclear Engineering • MSC01 1120 • The University of New Mexico • Albuquerque, NM 87131
505 277.5431 Phone • 505 277.5433 Fax • chne@unm.edu • www-chne.unm.edu

NEW MEXICO STATE UNIVERSITY

PhD & MS Programs in Chemical Engineering

Faculty and Research Areas

- **Paul K. Andersen,** Associate Professor and Associate Department Head (University of California, Berkeley) *Transport Phenomena, Electrochemistry, Environmental Engineering*
- **Shuguang Deng,** Professor (University of Cincinnati) *Advanced Materials for Sustainable Energy and Clean Water, Adsorption, and Membrane Separation Processes*
- **Abbas Ghassemi,** Professor and Director of the Institute for Energy and the Environment (New Mexico State University) *Risk-Based Decision Making, Environmental Studies Pollution Prevention, Energy Efficiency and Process Control*
- **Jessica Houston,** Assistant Professor (Texas A&M University) *Biomedical Engineering, Biophotonics, Flow Cytometry*
- **Charles L. Johnson,** Professor (Washington University-St. Louis) *High Temperature Polymers*
- **Richard L. Long,** Professor (Rice University) *Transport Phenomena, Biomedical Engineering, Separations, Kinetics, Process Design, Safety*
- **Hongmei Luo,** Assistant Professor *(Tulane University) Electrodeposition, Nanostructured Materials, Metal Oxide, Nitride, Composite Thin Films, Magnetism, Photocatalysts and Photovoltaics*
- **Martha C. Mitchell,** Professor and Head *(University of Minnesota) Molecular Modeling of Adsorption in Nanoporous Materials, Thermodynamic Analysis of Aerospace Fuels, Statistical Mechanics*
- **Stuart H. Munson-McGee,** Professor (University of Delaware) *Advanced Materials, Materials Processing*
- **David A. Rockstraw,** Professor (University of Oklahoma) *Kinetics and Reaction Engineering, Process Design*

For Application and Additional Information

Internet • http://chemeng.nmsu.edu/

Telephone • (575) 646-1214 E-mail • chemeng@nmsu.edu

PO Box 30001, MSC 3805 • Department of Chemical Engineering
New Mexico State University • Las Cruces, NM 88003

LOCATION

Southern New Mexico
350 days of sunshine a year

New Mexico State University is an Equal Opportunity Affirmative Action Employer

UNIVERSITY OF NOTRE DAME

CHEMICAL AND BIOMOLECULAR ENGINEERING

Ranked among the Top 20 Universities

DEPARTMENT: We are developing the next generation of research leaders. Our program is characterized by the close interaction between faculty and students and focus' on cutting-edge, interdisciplinary research that is both academically interesting and industrially relevant.

FACULTY RESEARCH

Z. Basar Bilgicer, Assistant Professor
Multivalent biomolecular interactions, thermodynamics & kinetics in biological systems

Paul W. Bohn, Professor
Chemical & biochemicals, lab-on-a-chip/intergrated microfluidics

Joan F. Brennecke, Keating-Crawford Professor & Director of Notre Dame Energy Center
Chemical systems, ionic Liquids, supercritical fluids, energy & environment, materials

H.-Chia Chang, Bayer Professor
Biological systems, chemicals, energy & environment, materials, microscale devices

Davide A. Hill, Associate Professor
Materials, fuel Cells, Computation & Theory

Prashant Kamat, Concurrent Professor
Chemical systems, fuel cells, energy & environment, materials/interfacial chemistry

Jeffrey C. Kantor, Professor
Integration of quantitative finance & control theory for process operations, application of stochastic programing & analysis in health care, Environment & Process operations

David T. Leighton, Jr., Professor
Complex fluids, Biochemical separations & flows

Edward J. Maginn, Professor
Chemical systems/catatlysis, ionic liquids, computation & theory, energy & environment, materials

Mark J. McCready, Professor & Chair
Chemical systems, multi-phase flow, fuel cells, energy & environment, microfludics, microscale devices

Paul J. McGinn, Professor
Chemical systems, fuel cells, catalysis, materials, energy & environment

Alexander S. Mukasyan, Research Professor
Chemical systems, materials, energy & environment, microscale devices,

William F. Schneider, Associate Professor
Chemical systems, energy & environment, materials, computational theory

Mark A. Stadtherr, Professor
Biological systems, chemical systems, computation & theory, energy & environment, materials

Eduardo E. Wolf, Professor
Chemical systems, materials, energy & environment

Elaine Zhu, Assistant Professor
Biological systems, chemical systems, energy & environment, materials, microscale devices

PROGRAMS AND FINANCIAL ASSISTANCE

The Department offers MS and PhD degree programs including financially attractive fellowships, assistantships, full-tuition fee waivers and insurance subsidies that are available to students pursuing either degree.

CONTACT INFO: On-Line Application: http://graduateschool.nd.edu/admissions Email: chegdept.1@nd.edu or Phone: 1-800-528-9487

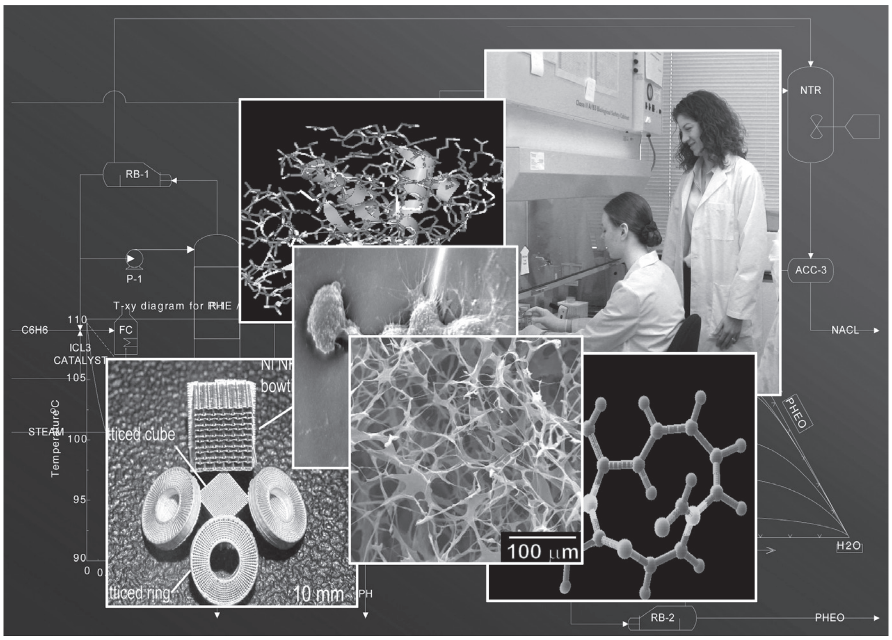
SCHOOL OF

Chemical Engineering

COLLEGE OF ENGINEERING, ARCHITECTURE AND TECHNOLOGY

GRADUATE PROGRAM

OSU's School of Chemical Engineering offers programs leading to M.S. and Ph.D. degrees. Qualified students receive financial assistance at nationally competitive levels.



Faculty

Heather D.N. Fahlenkamp
(PH.D., OKLAHOMA STATE UNIVERSITY)

Gary L. Foutch
(PH.D., UNIVERSITY OF MISSOURI-ROLLA)

Khaled A.M. Gasem
(PH.D., OKLAHOMA STATE UNIVERSITY)

Karen A. High
(PH.D., PENNSYLVANIA STATE UNIVERSITY)

Martin S. High
(PH.D., PENNSYLVANIA STATE UNIVERSITY)

A.J. Johannes
(PH.D., UNIVERSITY OF KENTUCKY)

Sundarajan V. Madihally
(PH.D., WAYNE STATE UNIVERSITY)

Joshua D. Ramsey
(PH.D., UNIVERSITY OF ILLINOIS)

R. Russell Rhinehart
(PH.D., NORTH CAROLINA STATE UNIVERSITY)

James E. Smay
(PH.D., UNIVERSITY OF ILLINOIS)

D. Alan Tree
(PH.D., UNIVERSITY OF ILLINOIS)

Jan Wagner
(PH.D., UNIVERSITY OF KANSAS)

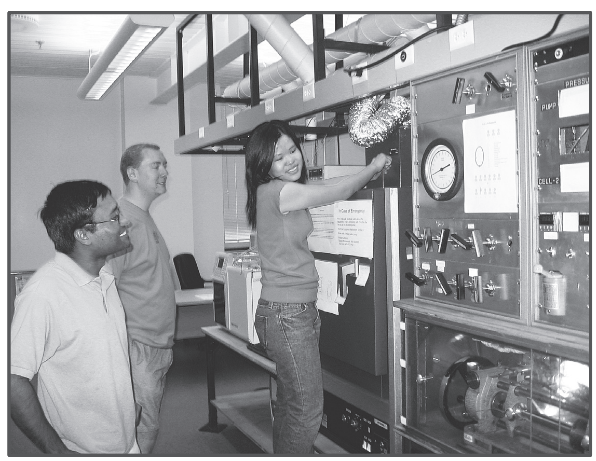
James R. Whiteley
(PH.D., OHIO STATE UNIVERSITY)

Research Areas

- ADSORPTION
- ARTIFICIAL INTELLIGENCE
- BIOCHEMICAL PROCESSES
- BIOFUELS
- BIOMATERIALS
- COLLOIDS / CERAMICS
- CO2 SEQUESTRATION
- ION EXCHANGE
- MOLECULAR DESIGN
- NANOMATERIALS
- OPTIMIZATION
- PHASE EQUILIBRIA
- POLYMERS
- PROCESS CONTROL
- PROCESS SIMULATION
- PRODUCT MODELING
- SOLID FREEFORM FABRICATION
- TISSUE ENGINEERING
- TRANSDERMAL DRUG DELIVERY

For Further Information

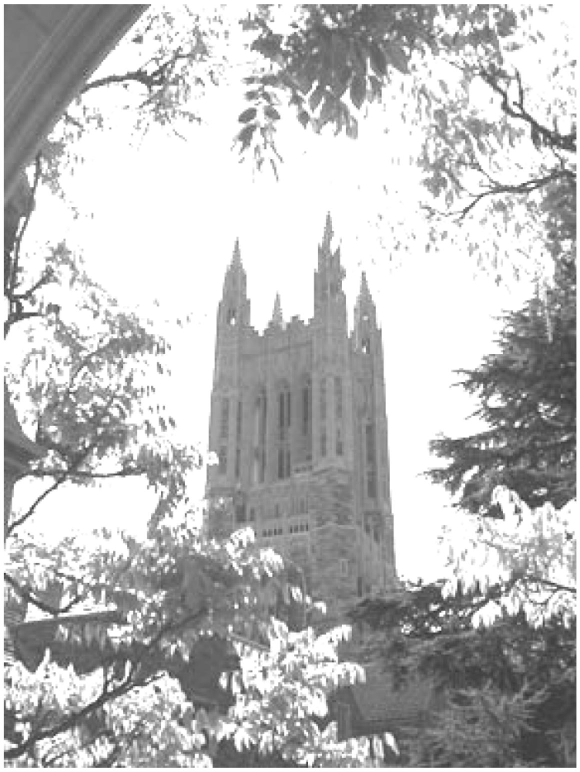
Dr. Khaled A.M. Gasem
School of Chemical Engineering
Oklahoma State University
Stillwater, OK 74078-5021
T 405 744 5280
gasem@okstate.edu
www.cheng.okstate.edu



cheng.okstate.edu

Princeton University

Ph.D. and M.Eng. Programs in Chemical and Biological Engineering



❑Applied and Computational Mathematics
Computational Chemistry and Materials
Systems Modeling and Optimization

❑Biotechnology
Biomaterials
Biopreservation
Cell Mechanics
Computational Biology
Protein and Enzyme Engineering
Tissue Engineering

❑Environmental and Energy Science and Technology
Art and Monument Conservation
Fuel Cell Engineering

❑Fluid Mechanics and Transport Phenomena
Biological Transport
Electrohydrodynamics
Flow in Porous Media
Granular and Multiphase Flow
Polymer and Suspension Rheology

❑Materials: Synthesis, Processing, Structure, Properties
Adhesion and Interfacial Phenomena
Ceramics and Glasses
Colloidal Dispersions
Nanoscience and Nanotechnology
Organic and Polymer Electronics
Polymers

❑Process Engineering and Science
Chemical Reactor Design, Stability, and Dynamics
Heterogeneous Catalysis
Process Control and Operations
Process Synthesis and Design

❑Thermodynamics and Statistical Mechanics
Complex Fluids
Glasses
Kinetic and Nucleation Theory
Liquid State Theory
Molecular Simulation

CBE Faculty

Ilhan A. Aksay	Yueh-Lin (Lynn) Loo
Jay B. Benziger	Celeste M. Nelson
Clifford P. Brangwynne	Athanassios Z. Panagiotopoulos
Mark P. Brynildsen	Rodney D. Priestley
Pablo G. Debenedetti	Robert K. Prud'homme
Christodoulos A. Floudas	Richard A. Register (Chair)
Yannis G. Kevrekidis	William B. Russel
Morton D. Kostin	Stanislav Y. Shvartsman
A. James Link	Sankaran Sundaresan

Affiliate Faculty

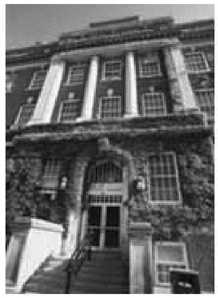
Emily A. Carter (Mechanical and Aerospace Engineering)
George W. Scherer (Civil and Environmental Engineering)
Howard A. Stone (Mechanical and Aerospace Engineering)

Write to:
Director of Graduate Studies
Chemical Engineering
Princeton University
Princeton, NJ 08544-5263

or call:
1-800-238-6169

or email:
cbegrad@princeton.edu

Please visit our website: www.princeton.edu/cbe


Chemical and Biological Engineering at

Rensselaer Polytechnic Institute

The Chemical and Biological Engineering Department at Rensselaer has long been recognized for its excellence in teaching and research. Its graduate programs lead to research-based M.S. and PhD. degrees and to a course-based M.E. degree. Programs are also offered in cooperation with the School of Management and Technology which lead to an M.S. in Chemical Engineering and to an MBA or the M.S. in Management. Owing to funding, consulting, and previous faculty experience, the department maintains close ties with industry. Department web site:

http://www.eng.rpi.edu/chme

Located in Troy, New York, Rensselaer is a private school with an enrollment of some 6000 students. Situated on the Hudson River, just north of New York's capital city of Albany, it is a three-hour drive from New York City, Boston, and Montreal. The Adirondack Mountains of New York, the Green Mountains of Vermont, and the Berkshires of Massachusetts are readily accessible. Saratoga, with its battlefield, racetrack, and Performing Arts Center (New York City Ballet, Philadelphia Orchestra, and jazz festival) is nearby.

Application materials and information from:
Graduate Admissions
Rensselaer Polytechnic Institute
Troy, NY 12180-3590
Telephone: 518-276-6216
e-mail: admissions@rpi.edu
http://admissions.rpi.edu/graduate/

Faculty and Research Interests

Georges Belfort, belfog@rpi.edu
Membrane separations; adsorption; biocatalysis; MRI; interfacial phenomena

B. Wayne Bequette, bequette@rpi.edu
Process control; fuel cell systems; biomedical systems

Cynthia H. Collins, ccollins@rpi.edu
Systems biology; protein engineering; intercellular communication systems; synthetic microbial ecosystems

Marc-Olivier Coppens, coppens@rpi.edu
Nature-inspired chemical engineering; mathematical & computational modeling; statistical mechanics; nanoporous materials synthesis; reaction engineering

Steven M. Cramer, crames@rpi.edu
Displacement, membrane and preparative chromatography; environmental research

Jonathan S. Dordick, dordick@rpi.edu
Biochemical engineering; biocatalysis; polymer science; bioseparations

Shekhar Garde, gardes@rpi.edu, *Department Head*
Macromolecular self-assembly, computer simulations, statistical thermodynamics of liquids, hydration phenomena

Ravi Kane, kaner@rpi.edu
Polymers; biosurfaces; biomaterials; nanomaterials, nanobiotechnology

Pankaj Karande, karanp@rpi.edu
Drug delivery; combinatorial chemistry; molecular modeling; high throughput screening

Lealon L. Martin, lealon@rpi.edu
Chemical and biological process modeling and design; optimization; systems engineering

Joel L. Plawsky, plawsky@rpi.edu
Electronic and photonic materials; interfacial phenomena; transport phenomena

Peter M. Tessier, tessier@rpi.edu
Protein-protein interactions, protein self-assembly and aggregation

Patrick T. Underhill, underhill@rpi.edu
Transport phenomena, multi-scale model development and applications to colloidal, polymer, and biological systems

Emeritus Faculty

Elmar R. Altwicker, altwie@rpi.edu
Spouted-bed combustion; incineration; trace pollutant kinetics

Henry R. Bungay III, bungah@rpi.edu
Wastewater treatment; biochemical engineering

Arthur Fontijn, fontia@rpi.edu
Combustion; high temperature kinetics; gas-phase reactions

William N. Gill, gilln@rpi.edu
Microelectronics; reverse osmosis; crystal growth; ceramic composites

Howard Littman, littmh@rpi.edu
Fluid/particle systems; fluidization; spouting bed; pneumatic transport

Peter C. Wayner, Jr., wayner@rpi.edu
Heat transfer; interfacial phenomena; porous materials

RICE

Chemical and Biomolecular Engineering @ RICE

Faculty

Sibani Lisa Biswal
(Stanford, 2004)

Walter Chapman
(Cornell, 1988)

Kenneth Cox
(Illinois, 1979)

Ramon Gonzalez
(Univ. of Chile, 2001)

George Hirasaki
(Rice, 1967)

Deepak Nagrath
(RPI, 2003)

Matteo Pasquali
(Minnesota, 2000)

Marc Robert
(Swiss Fed. Inst. Tech., 1980)

Laura Segatori
(UT Austin, 2005)

Rafael Verduzco
(Caltech, 2003)

Michael Wong
(MIT, 2000)

Kyriacos Zygourakis
(Minnesota, 1981)

Joint Appointments

Pulickel Ajayan
(Northwestern, 1989)

Cecilia Clementi
(Intl. Schl. Adv. Studies, 1998)

Vicki Colvin
(UC Berkeley, 1994)

Anatoly Kolomeisky
(Cornell, 1998)

Antonios Mikos
(Purdue, 1988)

Ka-Yiu San
(Caltech, 1984)

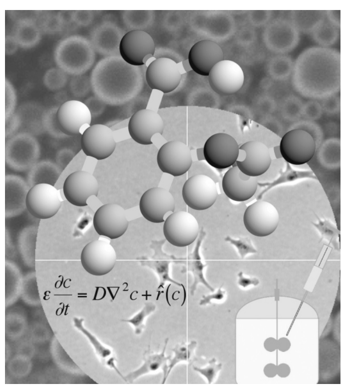
Jennifer West
(UT Austin, 1996)

THE UNIVERSITY

- Rice is a leading research university - small, private, and highly selective - distinguished by a collaborative, highly interdisciplinary culture.
- State-of-the-art laboratories, internationally renowned research centers, and one of the country's largest endowments support an ideal learning and living environment.
- Located only a few miles from downtown Houston, it occupies an architecturally distinctive, 300-acre campus shaded by nearly 4,000 trees.

THE DEPARTMENT

- Offers Ph.D., M.S., and M.Ch.E. degrees.
- Provides 12-month stipends and tuition waivers to full-time Ph.D. students.
- Currently has 74 graduate students (69 Ph.D. and 5 M.Ch.E.).
- Emphasizes interdisciplinary studies and collaborations with researchers from Rice and other institutions, national labs, the Texas Medical Center, NASA's Johnson Space Center, and R&D centers of petrochemical companies.



FACULTY RESEARCH AREAS

Advanced Materials and Complex Fluids
Synthesis and characterization of nanostructured materials, catalysis, nano- and microfluidics, self-assembling systems, hybrid biomaterials, rheology of nanostructured liquids, polymers, carbon nanotubes, interfacial phenomena, emulsions, and colloids.

Biosystems Engineering
Metabolic engineering, systems biology, nutritional systems biology, protein engineering, cellular and tissue engineering, microbial fermentations, analysis and design of gene networks, cellular reprogramming, and cell population heterogeneity.

Energy and Sustainability
Transport and thermodynamic properties of fluids, biofuels, CO_2 sequestration, biochar, gas hydrates, enhanced oil recovery, reservoir characterization, and pollution control.

For more information and graduate program applications, write to:
Chair, Graduate Admissions Committee
Chemical and Biomolecular Engineering, MS-362
Rice University, P.O. Box 1892
Houston, TX 77251-1892

Or visit our web site at http://www.rice.edu/chbe

Chemical Engineering at The University of Rochester

The University of Rochester is located in scenic upstate New York in an ideal setting to study, work, and grow intellectually. Through our M.S. and Ph.D. programs, students learn to apply key principles from chemistry, physics, and biology to address grand challenges facing society. We have outstanding laboratory research facilities, well supported infrastructure, and we offer competitive fellowship packages.

Graduate Studies & Research Programs

Advanced Materials

- Liquid Crystals
- Colloids & Surfactants
- Functional Polymers
- Inorganic/Organic Hybrids

Nanotechnology

- Thin Film Devices
- Photonics & Optoelectronics
- Nanofabrication
- Display Technologies

Clean Energy

- Fuel Cells
- Solar Cells
- Biofuels
- Green Engineering

Biotechnology

- Biomass Conversion
- Stem Cell Engineering
- Drug Delivery
- Biosensing

Faculty

M. ANTHAMATTEN
Ph.D., MIT, 2001
macromolecular self-assembly, shape memory polymers, vapor deposition, fuel cells

D. BENOITT
Ph.D., Colorado, 2006
rational design, synthesis, characterization, and employment of materials to treat diseases or control cell behavior

S. H. CHEN
Ph.D., Minnesota, 1981
polymer science, organic materials for photonics and electronics, liquid crystal and electroluminescent displays

E. H. CHIMOWITZ
Ph.D., Connecticut, 1982
supercritical fluid adsorption, molecular simulation of transport in disordered media, statistical mechanics

D. R. HARDING
Ph.D., Cambridge, 1986
chemical vapor deposition, mechanical and transport properties, advanced aerospace materials

S. D. JACOBS
Ph.D., Rochester, 1975
optics, photonics, and optoelectronics, liquid crystals, magnetorheology

J. JORNE
Ph.D., California (Berkeley), 1972
electrochemical engineering, fuel cells, microelectronics processing, electrodeposition

L. J. ROTHBERG
Ph.D., Harvard, 1984
organic device science, light-emitting diodes, display technology, biological sensors

A. SHESTOPALOV
Ph.D., Duke, 2009
Development of new unconventional fabrication and patterning techniques and their use in preparation of functional micro– and nanostructured devices

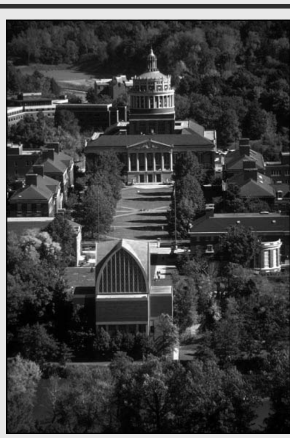
Y. SHAPIR
Ph.D., Tel Aviv (Israel), 1981
critical phenomena, transport in disordered media, scaling behavior of growing surfaces

C. W. TANG
Ph.D., Cornell, 1975
organic electronic devices, flat-panel display technology

J. H. DAVID WU
Ph.D., MIT, 1987
bone marrow tissue engineering, stem cell and lymphocyte cultures, enzymology of biomass energy process

H. YANG
Ph.D., Toronto, 1998
nanostructured materials, magnetic nanocomposites, fuel cell electrocatalysts, ionic liquids, and bionanotechnology

M. Z. YATES
Ph.D., Texas, 1999
colloids and interfaces, supercritical fluids, microemulsions, molecular sieves, fuel cells



Chemical Engineering Graduate Studies

http://www.che.rochester.edu

Department of Chemical Engineering
University of Rochester
206 Gavett Hall
Rochester, NY 14627
(585) 275-4913
chegradinfo@che.rochester.edu

URChE

HAJIM
SCHOOL OF ENGINEERING & APPLIED SCIENCES
UNIVERSITY *of* ROCHESTER

Master's of Science

Alternative Energy

HAJIM
SCHOOL OF ENGINEERING
& APPLIED SCIENCES
UNIVERSITY of ROCHESTER

The faculty at the University of Rochester have established strong research programs in advanced materials, biotechnology, and nanotechnology – the intellectual foundations for graduate education leading to Master's degrees. At the technological front, members of the Chemical Engineering faculty conduct research and teach courses highly relevant to alternative energy. Graduate-level courses and active research programs are underway in fuel cells, solar cells, and biofuels.

This program is designed for graduate students with a Bachelor's degree in engineering or science, who are interested in pursuing a technical career in alternative energy. Courses and research projects will focus on the fundamentals and applications of the generation, storage, and utilization of various forms of alternative energy as well as their impact on sustainability and energy conservation.

FACULTY and RESEARCH PROGRAMS

Fundamentals

M. ANTHAMATTEN
Ph.D., MIT, 2001

S. H. CHEN
Ph.D., Minnesota, 1981

E. H. CHIMOWITZ
Ph.D., Connecticut, 1982

D. FOSTER
Ph.D., Rochester, 1999

T. D. KRAUSS
Ph.D., Cornell, 1998

Biofuels

J. H. DAVID WU
Ph.D., MIT., 1987

Nuclear Energy

W-U. SCHRÖDER
Ph.D., Darmstadt, 1971

Fuel Cells and Battery

M. ANTHAMATTEN
Ph.D., MIT, 2001

J. LI
Ph.D., Washington, 1953

H. YANG
Ph.D., Toronto, 1998

M. Z. YATES
Ph.D., Texas, 1999

J. JORNE
Ph.D., California (Berkeley), 1972

Solar Cells

M. ANTHAMATTEN
Ph.D., MIT, 2001

S. H. CHEN
Ph.D., Minnesota, 1981

T. D. KRAUSS
Ph.D., Cornell, 1998

C. W. TANG
Ph.D., Cornell, 1975

H. YANG
Ph.D., Toronto, 1998

http://www.che.rochester.edu/altenergy.htm

Alternative Energy
University of Rochester
206 Gavett Hall
Rochester, NY 14627
(585) 275-4913
chegradinfo@che.rochester.edu

USC UNIVERSITY OF SOUTHERN CALIFORNIA

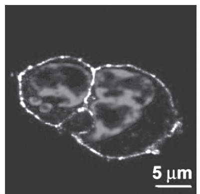
Mork Family

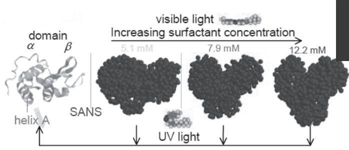
Department of Chemical Engineering and Materials Science

PhD Programs in Chemical Engineering, Petroleum Engineering, and Materials Science

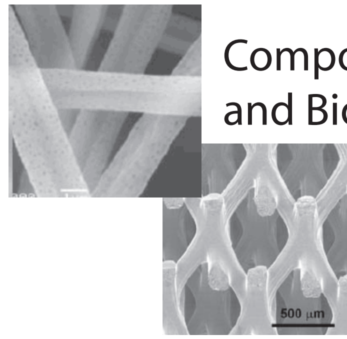
Active Research Areas:

Biomolecular Engineering

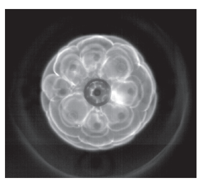


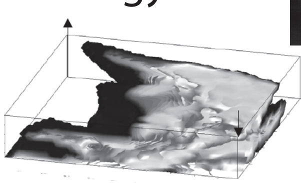


Composites and Biomaterials

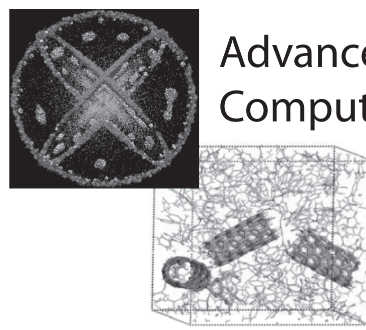


Sustainability and Energy

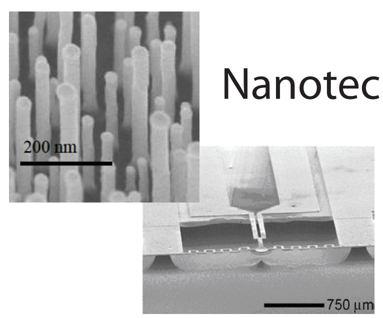




Advanced Computation



Nanotechnology



Academic and Research Highlights:

- PhD degrees offered: Chemical Engineering, Materials Science and Petroleum Engineering
- 100% of tuition and fees are covered for PhD students
- Over 30 tenured and tenure-track faculty
- Research is supported through federal grants and awards (NSF, NIH, DoD, DoE), industry partnerships (Chevron, Lockheed-Martin, Boeing), and foundations (Gates, Alfred Mann)
- Extensive core facilities, such as the Keck Photonics Facility (Class 100 cleanroom) and the Center for Electron Microscopy and Micro-Analysis.

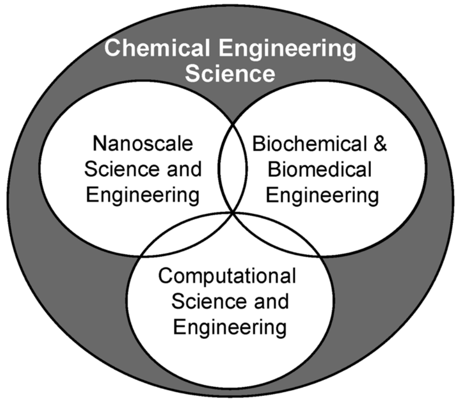
For more information:
http://chems.usc.edu

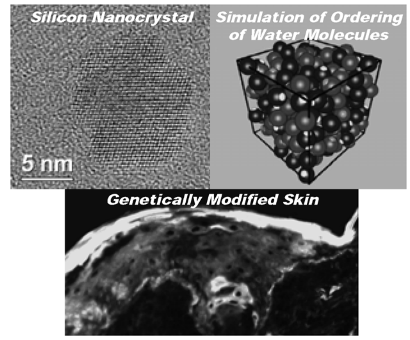
USC Viterbi
School of Engineering

University at Buffalo
The State University of New York

Chemical and Biological Engineering

Integrative Research at the Leading Edge of Chemical and Biological Engineering





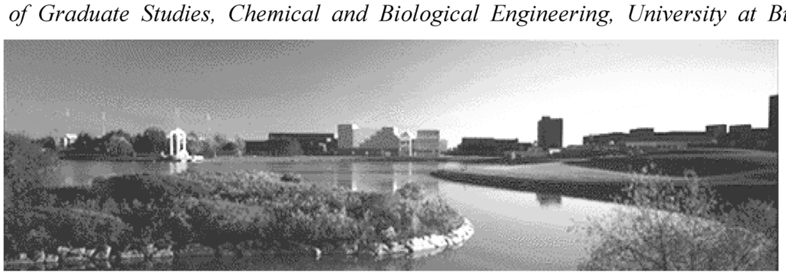
Faculty

Paschalis Alexandridis • *self-assembly, complex fluids, soft materials, nanomaterials, amphiphilic polymers, biopolymers*
Stelios T. Andreadis • *stem cells, cardiovascular and skin tissue engineering, wound healing, controlled protein and gene delivery*
Chong Cheng • *polymer-drug conjugates, nanomaterials by mini/microemulsion, biodegradable polymers and nanostructures*
Jeffrey R. Errington • *molecular simulation, statistical thermodynamics, interfacial phenomena*
Mattheos Koffas • *metabolic engineering, bioinformatics, natural products*
David A. Kofke • *molecular modeling and simulation*
Michael Lockett • *multi-phase flow and mass transfer in process equipment, distillation, air separation*
Carl R. F. Lund • *heterogeneous catalysis, chemical kinetics, reaction engineering*
Sriram Neelamegham • *biomedical engineering, cell and molecular biomechanics, systems biology*
Johannes M. Nitsche • *transport phenomena, dermal absorption, biological pore and membrane permeability*
Sheldon Park • *protein engineering, directed evolution, structural bioinformatics, and simulations*
Eli Ruckenstein • *surface phenomena, thermodynamics of large molecule solutions, interaction forces in nanosystems, protein folding and defolding, hydrophobic bonding*
Michael E. Ryan • *polymer and ceramics processing, rheology, non-Newtonian fluid mechanics*
Harvey G. Stenger, Jr. • *environmental applications of catalysis, hydrogen production, fuel cells*
Mark T. Swihart • *nanoparticle synthesis and applications, chemical kinetics, modeling reacting flows*
Esther S. Takeuchi • *energy storage, novel materials, reactivity at interfaces*
Marina Tsianou • *molecularly engineered materials, self-assembly, interfacial phenomena, controlled crystallization, biomimetics*
E. (Manolis) S. Tzanakakis • *stem cells, pancreatic tissue engineering, cardiac tissue engineering, biochemical engineering*

Chemical and Biological Engineering faculty participate in many interdisciplinary centers and initiatives including The Center of Excellence in Bioinformatics and Life Sciences, The Center for Computational Research, The Institute for Lasers, Photonics, and Biophotonics, The Center for Spin Effects and Quantum Information in Nanostructures, The Center for Advanced Molecular Biology and Immunology, and The Center for Advanced Technology for Biomedical Devices

http://www.cbe.buffalo.edu

For more information and an application, go to **http://www.cbe.buffalo.edu**, *e-mail cegrad@buffalo.edu, or write to Director of Graduate Studies, Chemical and Biological Engineering, University at Buffalo (SUNY), Buffalo, New York, 14260-4200*



All Ph.D. students are fully supported as research or teaching assistants. Additional fellowships sponsored by the State University of New York, the National Science Foundation, Praxair, Inc., and other organizations are available to exceptionally well-qualified applicants.

University of Tennessee

Recent advances in the life sciences and nanotechnology, as well as the looming energy crisis, have brought chemical engineering education to the threshold of significant changes. The Department of Chemical and Biomolecular Engineering (CBE) at the University of Tennessee has embraced these changes in order to meet global challenges in health care, the environment, renewable energy sources, national security and economic prosperity. Partnerships with other disciplines at UT, such as medical, life, and physical sciences, as well as the College of Business Administration and Oak Ridge National Laboratory (ORNL), help to create exceptional research opportunities for graduate students in CBE and place our students in a position to develop leadership roles in the vital technologies of the future.

Faculty and Research Interests

Paul Bienkowski (Purdue) -- Thermodynamics, environmental biotechnology, sustainable energy

Eric Boder (Illinois) -- Protein engineering, immune engineering, molecular bioengineering and biotechnology

Barry Bruce (Berkeley) -- Molecular chaperones, protein transport, bioenergy production

Chris Cox (Penn State) -- Bioenergy production, systems biology and metabolic engineering, environmental biotechnology

Wei-Ren Chen (MIT) -- Neutron scattering, advanced materials

Robert Counce (Tennessee) -- Industrial separations, process design, green engineering

Mark Dadmun (UMass) -- Polymer engineering, advanced materials

Brian Davison (CalTech) -- Systems biology, bioenergy production

Mitch Doktycz (Illinois-Chicago) -- Synthetic biology, nanobiotechnology

Paul Dalhaimer (Penn) -- Cytoskeleton biophysics, drug delivery, statistical mechanics, biophysical engineering

Brian Edwards (Delaware) -- Nonequilibrium thermodynamics, complex fluids, fuel cells

Paul Frymier (Virginia) -- Environmental biotechnology, sustainable energy production

Douglas Hayes (Michigan) -- Biocatalysis, bioseparations, colloids

David Joy (Oxford) -- Environmental microscopy, nanophase materials

Michael Kilbey (Minnesota) -- Interface engineering, soft materials

Ramki Kalyanaraman (NC State) -- Thin films, functional nanomaterials, phase transformation, self-assembly & self-organization

Bamin Khomami (Illinois) -- Micro- and nanostructured materials, complex fluids, multiscale modeling

David Keffer (Minnesota) -- Molecular simulation, advanced materials, fuel cells

Stephen Paddison (Calgary) -- PEM fuel cells, statistical mechanics, multiscale modeling

Cong Trinh (Minnesota) -- Inverse metabolic engineering, synthetic biology, bioenergy production

Tse-Wei Wang (MIT) -- Process modeling/control, bioinformatics, data mining

Thomas Zawodzinski (SUNY-Buffalo) -- Fuel cells, batteries, electrochemistry, transport phenomena

http://www.engr.utk.edu/cbe/

The UTK campus is located in the heart of Knoxville in beautiful east Tennessee, minutes from the Great Smoky Mountains National Park and surrounded by six lakes. Opportunities for outdoor recreation abound and are complemented by the diverse array of cultural activites afforded by our presence in the third largest city in Tennessee.

Chemical and Biomolecular Engineering at UT-Knoxville offers M.S. and Ph.D. degrees with financial assistance including full tuition and competitive stipends.

Chemical & Biomolecular Engineering
419 Dougherty Engineering Building
Knoxville, TN 37996-2200
Phone: (865) 974-2421
Email: cheinfo@utk.edu

THE UNIVERSITY of TENNESSEE UT
KNOXVILLE

Chemical Engineering at

Tennessee Tech University

Faculty

Pedro E. Arce, *Professor and Chair*
Ph.D., Purdue University, 1990
Electrokinetics, Nano Structured Soft Materials for Electrophoresis, Tissue Scaffolds & Drug Delivery, Non-thermal Plasma High Oxidation Processes

Joseph J. Biernacki, *Professor*
Dr. Eng., Cleveland State University, 1988
Cementious Systems, Micro-fluidics, Electronic and Structural Materials

Ileana C. Carpen, *Assistant Professor*
Ph.D., California Institute of Technology, 2005
Microrheology of Materials, Flow Stability of Complex Fluids, Colloidal Dispersions, Transport in Biological Systems

Vinten Diwakar, *Adjunct Professor*
Ph.D., Tennessee Tech University, 2009
Simulation of Electrochemical Systems, Electrolytes in Porous Media, Engineering Education.

David Elizandro, *Professor*
Ph.D., University of Arkansas, 1973
Engineering Optimization, Digital Signal Processing, Technology in Engineering Education.

Mario Oyanader, *Instructor*
Ph.D., Florida State University, 2004
Electrokinetic Soil Cleaning, Chemical Environmental Processes, Water Resource Management

Cynthia A. Rice-York, *Assistant Professor*
Ph.D., University of Illinois at Urbana-Champaign, 2000
Fuel Cells, Electrocatalysis

Holly A. Stretz, *Assistant Professor*
Ph.D., Univ. of Texas at Austin, 2005
Nanocomposite Structure and Modeling, High Temperature Materials and Ablatives, Polymer Processing

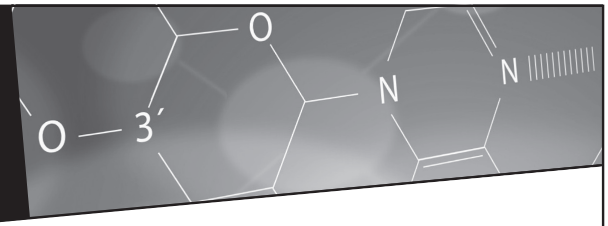
Donald P. Visco, Jr., *Professor*
Ph.D., University at Buffalo, SUNY, 1999
Computer-Aided Molecular Design, Experimental and Thermodynamic Modeling.

TTU's Chemical Engineering Department blends scholarship and research with advanced studies, offering excellent opportunities to graduate students. Our program offers an M.S. in Chemical Engineering and a Ph.D. in Engineering with a concentration in Chemical Engineering. The relatively small size of the program and friendly campus atmosphere promote close interaction among students and faculty. Research is sponsored by NSF, DOE, NASA, DOD, and state and private sources among others. Faculty members work closely with colleagues in Electrical Engineering, Environmental and Civil Engineering, Mechanical Engineering, Chemistry, Biology, and Manufacturing and Industrial Technology at TTU, as well as maintain strong collaboration with TTU's Centers of Excellence and other leading institutions and national laboratories to build a unique and effective environment for graduate research, learning, and well-rounded training.

Located in one of the most beautiful geographical regions in Tennessee, Cookeville is the home of Tennessee Tech University. A warm and welcoming community surrounded by parks, lakes and mountains, Cookeville is located a little more than an hour from three of Tennessee's metro areas: Nashville, Chattanooga, and Knoxville.

FOR MORE INFORMATION, contact:
TTU Chemical Engineering Department ● P.O. Box 5013 ● Cookeville, TN 38505-0001 ● che@tntech.edu ● Phone (931) 372-3297
Fax (931) 372-6352 ● Also, visit us on the World Wide Web at: http://www.tntech.edu/che

CHEMICAL & ENVIRONMENTAL
ENGINEERING



FACULTY

ABDUL-MAJEED AZAD, PROFESSOR
Ph. D., University of Madras, India
Nanomaterials & Ceramics Processing, Solid Oxide Fuel Cells

MARIA R. COLEMAN, PROFESSOR
Ph. D., University of Texas at Austin
Membrane Separations, Bioseparations

JOHN P. DISMUKES, PROFESSOR
Ph. D., University of Illinois
Materials Processing, Managing Technological Innovation

ISABEL C. ESCOBAR, PROFESSOR
Ph. D., University of Central Flordia
Membrane Fouling and Membrane Modifications

SALEH JABARIN, PROFESSOR
Ph. D., University of Massachusetts
Polymer Physical Properties, Orientation & Crystallization

DONG-SHIK KIM, ASSOCIATE PROFESSOR
Ph. D., University of Michigan
Biomaterials, Metabolic Pathways, Biomass Energy

YAKOV LAPITSKY, ASSISTANT PROFESSOR
Ph.D., University of Delaware
Colloid & Polymer Science, Drug Delivery

STEVEN E. LEBLANC, PROFESSOR
Ph. D., University of Michigan
Process Control, Chemical Engineering Education

G. GLENN LIPSCOMB, PROFESSOR AND CHAIR
Ph. D., University of California at Berkeley
Membrane Separations, Alternative Energy, Education

BRUCE E. POLING, PROFESSOR
Ph. D., University of Illinois
Thermodynamics and Physical Properties

CONSTANCE A. SCHALL, PROFESSOR
Ph. D., Rutgers University
Biomass Conversion, Enzyme kinetics, Crystallization

SASIDHAR VARANASI, PROFESSOR
Ph. D., State University of New York, Buffalo
Bio- & Thermo-chemical Biomass Conversion,
Colloid & Interfacial Phenomena

SRIDHAR VIAMAJALA, ASSISTANT PROFESSOR
Ph.D. Washington State
Biofuels from Algae and Lignocellulose, Bioprocessing

The Department of Chemical & Environmental Engineering at The University of Toledo offers graduate programs leading to M.S. and Ph.D. degrees. We are located in state of the art facilities in Nitschke Hall and our dynamic faculty offer a variety of research opportunities in contemporary areas of chemical engineering.

SEND INQUIRIES TO:
Graduate Studies Advisor
Chemical & Environmental Engineering
The University of Toledo
College of Engineering
2801 W. Bancroft Street
Toledo, Ohio 43606-3390

419.530.8080 • *www.che.utoledo.edu*
cheedept@eng.utoledo.edu

COLLEGE OF ENGINEERING
THE UNIVERSITY OF TOLEDO

EN 583 0410

Engineering the World

The University of Tulsa

The University of Tulsa is Oklahoma's oldest and largest independent university. Approximately 4,200 students pursue more than 70 major fields of study and graduate programs in more than 25 disciplines.

Tulsa, Oklahoma

Off-campus activities abound in Tulsa, one of the nation's most livable cities. Our temperate climate, with four distinct seasons, is perfect for year-round outdoor activities. With a metropolitan population of 888,000, the city of Tulsa affords opportunities for students to gain internship and work experience in its dynamic data processing, petroleum, medical, and financial industries. One can also enjoy world-class ballet, symphony and theatre performances, and exhibits in the cultural community. Annual events include Mayfest, Oktoberfest, the Chili Cook-off and Bluegrass Festival, the Tulsa Run, and the Jazz and Blues festivals.

Chemical Engineering at TU

TU enjoys a solid international reputation for expertise in the energy industry, and offers materials, environmental and biochemical programs. The department places particular emphasis on experimental research, and is proud of its strong contact with industry.

The department offers a traditional Ph.D. program and three master's programs:

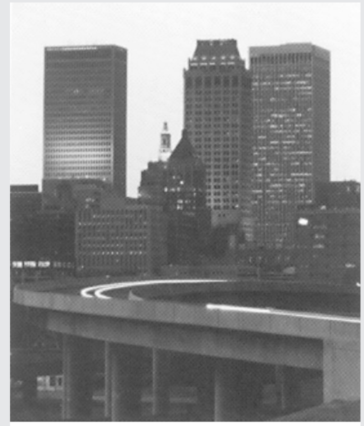
- Master of Science degree (thesis program)
- Master of Engineering degree (a professional degree that can be completed in 18 months without a thesis)
- Special Master's degree for nonchemical engineering undergraduates

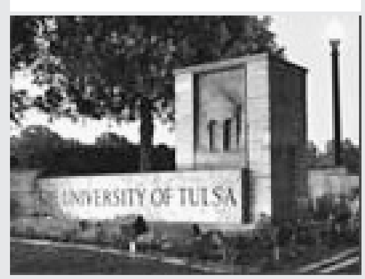
Financial aid is available, including fellowships and research assistantships.

The Faculty

S.A. Cremaschi • Engineering complex systems, optimization under uncertainty
D.W. Crunkleton • Alternative energy, transport phenomena
L.P. Ford • Kinetics of dry etching of metals, surface science
T. W. Johannes • Directed evolution, biocatalysis, biosynthesis, metabolic engineering
F.S. Manning • Industrial pollution control, surface processing of petroleum
C.L. Patton • Thermodynamics, applied mathematics
G.L. Price • Zeolites, heterogeneous catalysis
K.L. Sublette • Bioremediation, biological waste treatment, ecological risk assessment
K.D. Wisecarver • Multiphase reactors, multiphase flows

Further Information
Graduate Program Director • Chemical Engineering Department
The University of Tulsa • 800 South Tucker Drive • Tulsa, Oklahoma 74104-3189
Phone (918) 631-2227 • Fax (918) 631-3268
E-mail: chegradadvisor@utulsa.edu • Graduate School application: 1-800-882-4723





Vanderbilt University

DEPARTMENT OF CHEMICAL AND BIOMOLECULAR ENGINEERING

Graduate Study Leading to the M.S. and Ph.D. Degrees

Graduate work in chemical engineering provides an opportunity for study and research at the cutting edge - to contribute to shaping a new model of what chemical engineering is and what chemical engineers do. At Vanderbilt University we offer a broad range of research opportunities in chemical and biomolecular engineering, with wide ranging opportunities for interdisciplinary work and professional development. Focus areas include:

- *Adsorption and nanoporous materials*
- *Alternative energy and biofuels*
- *Biomaterials and tissue engineering*
- *Computational molecular engineering and nanoscience*
- *Metabolic engineering*
- *Microelectronic and ultra-high temperature materials*
- *Nanoparticles for drug and gene delivery*
- *Surface modification and molecular self-assembly*

To find out more visit:

http://www.che.vanderbilt.edu/

Vanderbilt, ranked in the top 20 nationally for its leadership in both research and teaching, is located on 330 park-like acres just one and one-half miles from downtown Nashville, one of the most vibrant and cosmopolitan mid-sized cities in the United States. Ten schools offer both an outstanding undergraduate and a full range of graduate and professional programs. With a prestigious faculty of more than 2,800 full-time and 300 part-time members, Vanderbilt attracts a diverse student body of approximately 6,500 undergraduates and 5,300 graduate and professional students from all 50 states and over 90 foreign countries.

Peter T. Cummings *(Ph.D., University of Melbourne)* Computational nanoscience and nanoengineering; molecular modeling of fluid and amorphous systems; parallel computing; cell-based models of cancer tumor growth

Kenneth A. Debelak *(Ph.D., University of Kentucky)* Catalytic reactions for renewable fuels; oscillations in bioreactors; Development of plant-wide control algorithms; intelligent process control

Scott A. Guelcher *(Ph.D., Carnegie Mellon University)* Biomaterials; bone tissue engineering; polymer synthesis and characterization; drug and gene delivery

G. Kane Jennings *(Ph.D., Massachusetts Institute of Technology)* Molecular and surface engineering; polymer thin films; solar energy conversion; tribology; fuel cells

Paul E. Laibinis *(Ph.D., Harvard University)* Self-assembly; surface engineering; interfaces; chemical sensor design; biosurfaces; nanotechnology

Matthew J. Lang *(Ph.D., University of Chicago)* Molecular and cellular biophysics; functional measurement of biological motors and cell machinery; instrumentation: optical tweezers, microscopy and single molecule fluorescence

M. Douglas LeVan *(Ph.D., University of California, Berkeley)* Novel adsorbent materials; adsorption equilibria; mass transfer in nanoporous materials; adsorption and membrane processes.

Clare McCabe *(Ph.D., University of Sheffield)* Molecular modeling of complex fluids and materials; biological self-assembly; molecular rheology and tribology; molecular theory and phase equilibria

Peter N. Pintauro *(Ph.D., University of California, Los Angeles)* Electrochemical engineering; membrane development for hydrogen, methanol, and alkaline fuel cells; ion uptake and transport models for ion-exchange membranes; organic electrochemical synthesis

Bridget R. Rogers *(Ph.D., Arizona State University)* Surfaces, interfaces, and films of microelectronic and ultra-high temperature materials; determination of process/property/performance relationships

Jamey D. Young *(Ph.D., Purdue University)* Metabolic engineering; systems biology; diabetes, obesity and metabolic disorders; tumor metabolism; autotrophic metabolism

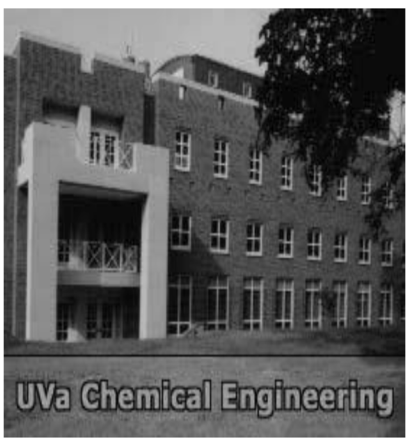
For more information:

Director of Graduate Studies
Department of Chemical and Biomolecular Engineering
Vanderbilt University • VU Station B 351604
Nashville, TN 37235-1604
Email: chegrad@vanderbilt.edu

University of Virginia

...fulfilling Thomas Jefferson's vision

Graduate Studies in Chemical Engineering



Graduate Admissions
Dept. of Chemical Engineering
102 Engineers' Way
P.O. Box 400741
University of Virginia
Charlottesville, VA 22904-4741
434-924-7778

E-mail:
cheadmis@virginia.edu

Visit our website:
www.che.virginia.edu

The educational philosophy of the department reflects a commitment to continuing the Jeffersonian ideal of students and faculty as equal partners in the pursuit and creation of knowledge.

Giorgio Carta, *PhD*, *University of Delaware*
Adsorption, ion exchange, protein chromatography, biochemical engineering

Robert J. Davis, *PhD, Stanford University*
Heterogeneous catalysis, reaction kinetics, conversion of renewable resources

Erik J. Fernandez, *PhD, University of California, Berkeley*
Purification and aggregation of protein therapeutics, molecular aspects of neurodegeneration

Roseanne M. Ford, *PhD, University of Pennsylvania*
Environmental remediation, microbial transport in porous media

David L. Green, *PhD, University of Maryland, College Park*
Reaction engineering of nanoparticles, rheology of complex nanoparticle suspensions

John L. Hudson, *PhD, Northwestern University*
Engineering complex dynamics in reacting systems: applications to electrochemistry, biology and medicine

Inchan Kwon, *PhD, California Institute of Technology*
Genetic engineering, gene therapy, and protein engineering: applications to treatment of neurodegenerative diseases and design of biocatalysts

Matthew Neurock, *PhD, University of Delaware*
Molecular modeling, computational heterogeneous catalysis, kinetics of complex reaction systems

John P. O'Connell, *PhD, University of California, Berkeley*
Molecular theory, thermodynamic modeling and process simulation with applications to separations and hydrogen manufacture

Michael R. Shirts, *PhD, Stanford University*
Molecular modeling, thermodynamics and statistical mechanics of complex fluids, pharmaceutical design, nanomolecular self-assembly

Chemical Engineering at Virginia Tech

Faculty . . .

Luke E.K. Achenie (Carnegie Mellon)
Modeling of chemical and biological systems

Donald G. Baird (Wisconsin)
Polymer processing, non-Newtonian fluid mechanics

David F. Cox (Florida)
Catalysis, ultrahigh vacuum surface science

Christopher J. Cornelius (Virginia Tech)
Hybrid organic-inorganic materials, sol-gel chemistry, self-assembly

Richey M. Davis (Princeton)
Colloids and polymer chemistry, nanostructured materials

William A. Ducker (Australian Natl. Univ.)
Colloidal forces, surfactant self-assembly, atomic force microscopy

Aaron S. Goldstein (Carnegie Mellon)
Tissue engineering, interfacial phenomena in bioengineering

Erdogan Kiran (Princeton)
Supercritical fluids, polymer science, high pressure techniques

Y.A. Liu (Princeton)
Pollution prevention and computer-aided design

Chang Lu (Illinois)
Microfluidics for single cell analysis, gene delivery

Eva Marand (Massachusetts)
Transport through polymer membranes, advanced materials for separations

Stephen M. Martin (Minnesota)
Soft materials, self-assembly, interfaces

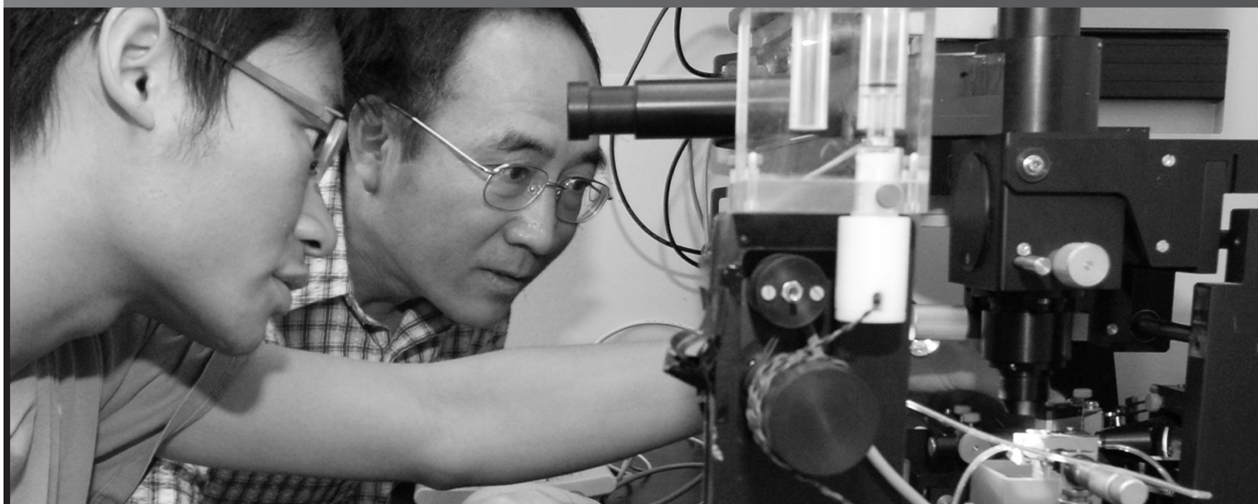
Abby W. Morgan (Illinois)
Tissue engineering, controlled release of proteins

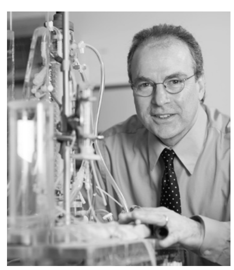
S. Ted Oyama (Stanford)
Heterogeneous catalysis and new materials

Padma Rajagopalan (Brown)
Polymeric biomaterials, cell and tissue engineering

John Y. Walz [Dept. Head] (Carnegie Mellon)
Colloidal stability, interparticle forces

For further information write or call the director of graduate studies or visit our webpage
Department of Chemical Engineering
133 Randolph Hall, Virginia Tech, Blacksburg VA 24061
Telephone: 540-231-5771 • Fax: 540-231-5022
e-mail: chegrad@vt.edu • http://www.che.vt.edu





Graduate Study in the Department of Energy, Environmental and Chemical Engineering

Washington University in St. Louis

Masters and Ph.D Programs

Dept. of Energy, Environmental & Chemical Engineering

The department has a focus on environmental engineering science, energy systems, and chemical engineering. The department provides integrated and multidisciplinary programs of scientific education. Our mission is accomplished by:

- Instilling a tradition of "life-long learning"
- A curriculum of fundamental education coupled with application in an advanced focal area and strengthened by our breadth in other disciplinary areas
- Participation in cutting-edge research with faculty and industrial partners
- Access to state-of-the-art facilities and instrumentation

The basic degree is an undergraduate degree in chemical engineering. Graduate degrees (Master of Science and Doctor of Philosophy) are offered in Energy, Environmental and Chemical Engineering on completion of a course of study and research work. Professional Masters degrees with tracks in Energy and Environmental Management, International Development are also offered. A minor is offered to undergraduate students interested in environmental engineering and can be selected by any engineering or science student. The program is also affiliated with the Environmental Studies Program.

R. Axelbaum - Nanoparticle Synthesis, Combustion Engineering

P. Biswas - Aerosol Science & Technology, Environmental & Energy Nanotechnology

D. Chen - Particle Measurement & Instrumentation, Aerosol Science Technology

M. Dudukovic - Multiphase Reaction Engineering, Tracer Methods, Environmental Engineering

J. Fortner - Aquatics, Environmental Chemistry of Nanomaterials

D. Giammar - Aquatic Chemistry, Water Quality Engineering, Fate & Transport of Inorganic Contaminants

J. Gleaves - Heterogeneous Catalysis, Surface Science, Microstructured Materials

R. Husar - Environmental Informatics, Aerosol Pattern & Trend Analysis

Y.S. Jun - Aquatic Processes, Molecular Issues in Chemical Kinetics

C. Lo - Aquatic Processes, Biomineral Structure & Reactivity at Environmental Interfaces

H. Pakrasi - Systems Biology

P. Ramachandran - Chemical Reaction Engineering, Boundary Element Methods

V. Subramanian - Multiscale Phenomena, Electrochemical Systems and Applied Mathematics

Y. Tang - Metabolomics, Systems Biology

J. Turner - Environmental Reaction Engineering, Air Quality Policy & Analysis, Aerosol Science & Technology

B. Williams - Aerosols, Global Climate Issues, Atmospheric Sciences

Graduate Admissions Committee, Washington University in St. Louis, **Department of Energy, Environmental and Chemical Engineering**
One Brookings Dr. • Campus Box 1180 • St. Louis, MO 63130-4899 • www.eec.wustl.edu • eec@wustl.edu • 314-935-6070 • Fax: 314-935-5464

UNIVERSITY OF WATERLOO

Graduate Study in Chemical Engineering

The Department of Chemical Engineering is one of the largest in Canada offering a wide range of graduate programs. Full-time and part-time M.A.Sc. programs are available. Full-time and part-time coursework M.Eng. programs are available. Ph.D. programs are available in all research areas.

Challenging Research in Novel Areas of Chemical Engineering:

Our professors offer research projects in:

- Nanotechnology and nano-materials
- Biomaterials with applications to drug delivery and tissue Engineering
- Biotechnology and Biochemical Engineering
- Catalysis
- Composite Materials
- Fuel Cells
- Green Reaction Engineering
- Interfacial Phenomena/Membrane Technology
- Polymer engineering
- Process Control and Statistics
- Separation Processes

FINANCIAL SUPPORT

for graduate students is available in the form of:

- *Research Assistantships*
- *Teaching Assistantships*
- *Entrance Scholarships*

RESEARCH GROUPS AND PROFESSORS:

1. **Biochemical and Biomedical Engineering:**
Bill Anderson, Marc Aucoin, Hector Budman, Pu Chen, Perry Chou, Frank Gu, Eric Jervis, Christine Moresoli, Raymond Legge, Michael Tam.

2. **Interfacial Phenomena, Colloids and Porous Media:**
John Chatzis, Pu Chen, Zhongwei Chen, Michael Fowler, Dale Henneke, Mario Ioannidis, Rajinder Pal, Mark Pritzker, Boxin Zhao.

3. **Green Reaction Engineering:**
Bill Anderson, Zhongwei Chen, Eric Croiset, Bill Epling, Michael Fowler, Flora Ng, Garry Rempel, Qinmin Pan, Mark Pritzker.

4. **Nanotechnology:**
Pu Chen, Zhongwei Chen, Frank Gu, Dale Henneke, Yuning Li, Leonardo Simon, Michael Tam, Ting Tsui, Boxin Zhao.

5. **Process Control, Statistics and Optimization:**
Hector Budman, Peter Douglas, Tom Duever, Ali Elkamel, Alex Penlidis, Mark Pritzker.

6. **Polymer Science and Engineering:**
Tom Duever, Xianshe Feng, Mike Fowler, Frank Gu, Neil McManus, Qinmin Pan, Alex Penlidis, Garry Rempel, Leonardo Simon, Joao Soares, Michael Tam, Costas Tzoganakis, Boxin Zhao.

7. **Separation Processes:**
John Chatzis, Pu Chen, Zhongwei Chen, Xianshe Feng, Christine Moresoli, Flora Ng, Qinmin Pan, Rajinder Pal, Mark Pritzker, Michael Tam.

ADMISSION REQUIREMENTS:

- Undergraduate Degree in Engineering or Science.
- FOR SCIENCE STUDENTS: No additional courses are required from applicants with an undergraduate degree in Science.

For further information, write or phone

The Associate Chair (Graduate Studies), Department of Chemical Engineering, University of Waterloo
Waterloo, Ontario, Canada N2L 3G1
Phone (519) 888-4567, ext. 32484 • Fax (519) 746-4979
e-mail at gradinfo.che@uwaterloo.ca
or visit our website at http://cape.uwaterloo.ca

West Virginia University

Faculty

Sushant Agarwal
West Virginia University

Brian J. Anderson
Massachusetts Institute of Technology

Debangsu Bhattacharyya
Clarkson University

Eugene V. Cilento, Dean
University of Cincinatti

Dady B. Dadyburjor
University of Delaware

Cerasela Z. Dinu
Max Planck Institute of Molecular Cell Biology and Genetics and Dresden University

Robin S. Farmer
University of Delaware

Rakesh K. Gupta, Chair
University of Delaware

Elliot B. Kennel
Ohio State University

David J. Klinke, II
Northwestern University

Edwin L. Kugler
Johns Hopkins University

Ruifeng Liang
Institute of Chemistry, CAS

Joseph A. Shaeiwitz
Carnegie Mellon University

Alfred H. Stiller
University of Cincinatti

Charter D. Stinespring
West Virginia University

Richard Turton
Oregon State University

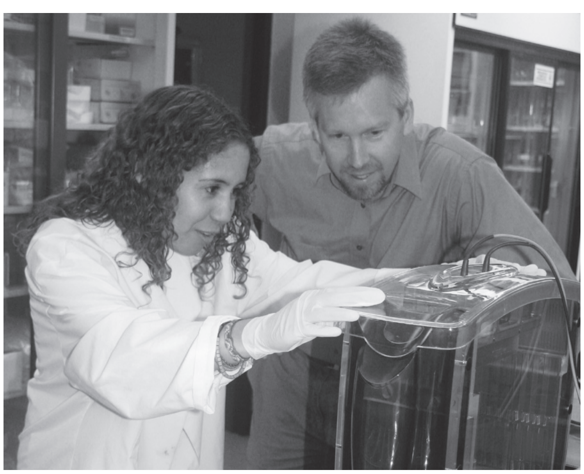
Ray Y. K. Yang
Princeton University

John W. Zondlo
Carnegie Mellon University

Come Explore

Chemical Engineering

MS and PhD Programs



http://www.che.cemr.wvu.edu

Research Areas Include:

Bioengineering, Systems Biology
Biomaterials, Tissue Engineering
Bionanotechnology, Biomimetics
Carbon Products from Coal
Catalysis and Reaction Engineering
Coal /Biomass Gasification
Coal/Biomass Liquefaction
Electronic Materials, Nanostructures
Fluid-Particle Sciences
Fuel Cells
Molecular Dynamics and Modeling
Nanocomposites, Nanoparticles
Natural-Gas Hydrates
Particle Coating / Agglomeration
Polymer Rheology
Separation Processes

Financial Aid

Research Assistantships
Fellowships
Bayer Fellowships
(includes internships)

For Application Information, Write

Professor Dady B. Dadyburjor
Graduate Admission Committee
Department of Chemical Engineering
PO Box 6102
West Virginia University
Morgantown, WV 26506-6102
304-293-2111
che-info@mail.wvu.edu


WORCESTER POLYTECHNIC INSTITUTE
Graduate Studies in CHEMICAL ENGINEERING
Bioengineering • Catalysis and Reaction Engineering
Nanomaterials Process Analysis, Control, and Safety • Sustainable and Green Engineering
MS and PhD Programs • Collaborative Environment • World-Class Faculty • State-of-the-Art Facilities
RESEARCH AREAS AND FACULTY
Bacterial Adhesion • Biomaterials • Nanobiotechnology
Terri A. Camesano, PhD, Pennsylvania State University
Separation Processes • Engineering Education
William M. Clark, PhD, Rice University
Catalysis and Reaction Engineering
as Applied to Fuel Cells and Hydrogen
Ravindra Datta, PhD, University of California, Santa Barbara
Catalysis and Surface Science • Metal Oxide Materials
Computational Chemistry
N. Aaron Deskins, PhD, Purdue University
Engineering Education • Teaching and Learning • Assessment
David DiBiasio, PhD, Purdue University
Transport in Chemical Reactors • Application of CFD to Catalyst
and Reactor Design • Microreactors
Anthony G. Dixon, PhD, University of Edinburgh
Analysis, Control and Safety of Chemical Processes
Environmental and Energy Systems • Process Performance Monitoring
Nikolaos K. Kazantzis, PhD, University of Michigan
Syntheses, Characterization and Application of Inorganic Membranes
with special emphasis on composite Pd and Pd alloy porous
metal membranes for hydrogen separation and membrane reactors
Yi Hua Ma, ScD, MIT
Applied Kinetics and Reactor Analysis • Particulate Synthesis
Water Purification Engineering
Robert W. Thompson, PhD, Iowa State University
Bionanotechnology • Bioseparations • BioMEMS Microfluidics
Microelectronic and Photonic Packaging
Susan Zhou, PhD, University of Califonia, Irvine
Worcester, New England's third largest city, is an hour from Boston, Providence, and Hartford. It has an active arts and cultural community, great restaurants, entertainment venues, and shopping centers. The region is known for its high concentration of life sciences–based companies and academic research centers.
WORCESTER POLYTECHNIC INSTITUTE 1865
WPI
To learn more or to apply, visit wpi.edu/+CHE
Department of Chemical Engineering • WPI
100 Institute Road • Worcester, MA • 01609 508-831-5250 • chemeng@wpi.edu

YALE

Department of Chemical & Environmental Engineering

Eric Altman, Ph.D. Pennsylvania

Menachem Elimelech,
Ph.D. Johns Hopkins

Gary Haller, Ph.D. Northwestern

Michael Loewenberg, Ph.D. Cal Tech

William Mitch, Ph.D. University of California

Chinedum Osuji, Ph.D. M.I.T.

Jordan Peccia,
Ph.D. University of Colorado

Lisa Pfefferle, Ph.D. Pennsylvania

Daniel Rosner, Ph.D. Princeton

André Taylor, Ph.D. University of Michigan

Paul Van Tassel,
Ph.D. University of Minnesota

Kyle Vanderlick,
Ph.D. University of Minnesota

Corey Wilson, Ph.D. Rice University

Julie Zimmerman,
Ph.D. University of Michigan

Joint Appointments

- **Thomas Graedel** (School of Forestry & Environmental Studies)
- **Kurt Zilm** (Chemistry)
- **Mark Saltzman** (Biomedical Engineering)

LUX ET VERITAS

Biomolecular Engineering
Catalysis
Chemical Reaction Engineering
Combustion
Complex Fluids
Energy
Environmental Engineering Microbiology
Environmental Physio-chemical Processes
Interfacial and Colloidal Phenomena
Membrane Separations
Materials Synthesis and Processing
Nanoparticles and Nanomaterials
Multiphase Transport Phenomena
Soft Nanomaterials
Surface Science
Sustainability
Water

Yale University
P. O. Box 208286
New Haven, CT 06520-8286
Phone: (203) 432-2222 • FAX: (203) 432-4387
http://www.eng.yale.edu/content/DPchemical engineering.asp

BRIGHAM YOUNG UNIVERSITY

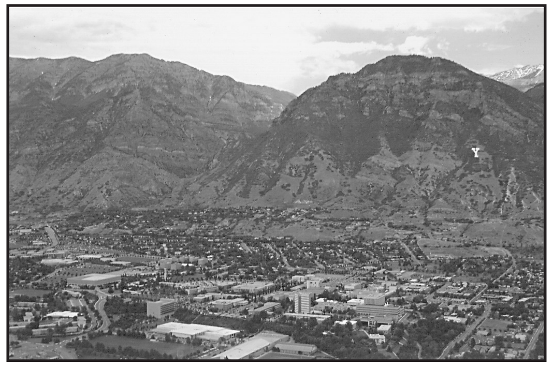
Graduate Studies in Chemical Engineering

M.S. and Ph.D. Degree Programs

Faculty and Research Interests

Morris D. Argyle *(Berkeley)* • heterogeneous catalysis
Larry L. Baxter *(BYU)* • combustion of fossil and renewable fuels
Bradley C. Bundy *(Stanford)* • protein production and engineering
Thomas H. Fletcher *(BYU)* • pyrolysis and combustion
John H. Harb *(Illinois)* • coal combustion, electrochemical engineering
William C. Hecker *(UC Berkeley)* • kinetics and catalysis
Thomas A. Knotts *(University of Wisconsin)* • molecular modeling
Randy S. Lewis (*MIT*) • biochemical and biomedical engineering
David O. Lignell *(Utah)* • computational reacting flow
William G. Pitt *(Wisconsin)* • materials science
Richard L. Rowley *(Michigan State)* • thermophysical properties
Kenneth A. Solen *(Wisconsin)* • biomedical engineering
Dean R. Wheeler *(Berkeley)* • molecular electrochemistry
W. Vincent Wilding *(Rice)* • thermodynamics, environmental engineering

Study in an uplifting, intellectual, social, and spiritual environment



Financial Support Available

For further information
See our website at: http://www.et.byu.edu/cheme/
Contact: Graduate Coordinator • Dept. of Chemical Engineering • P.O. Box 24100
Brigham Young University • Provo, UT 84602 • (801) 422-2586

BYU

BUCKNELL UNIVERSITY

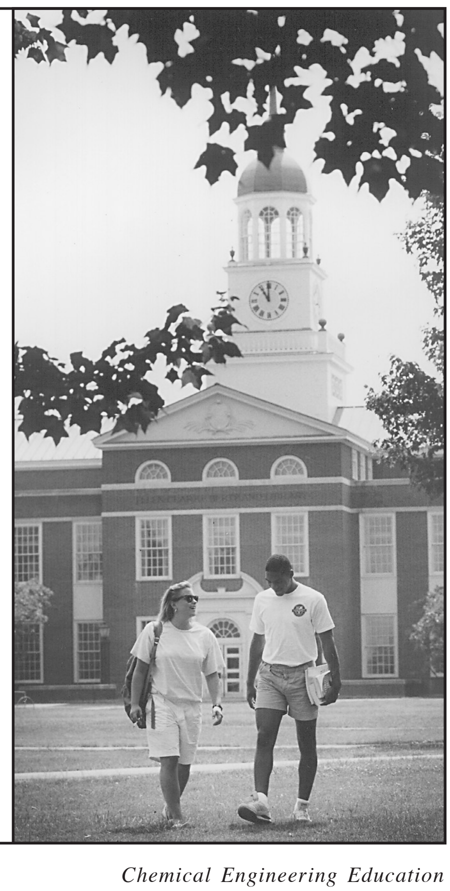
Master of Science in Chemical Engineering

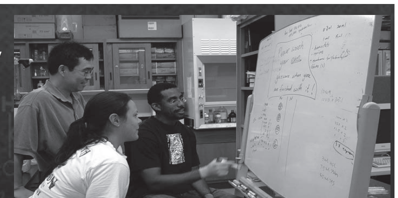
Bucknell is a highly selective private institution that combines a nationally ranked undergraduate engineering program with the rich learning environment of a small liberal arts college. For study at the Master's level, the department offers state-of-the-art facilities for both experimental and computational work, and faculty dedicated to providing individualized training and collaboration in a wide array of research areas.

Nestled in the heart of the scenic Susquehanna Valley in central Pennsylvania, Lewisburg is located in an ideal environment for a variety of outdoor activities and is within a three-hour drive of several metropolitan centers, including New York, Philadelphia, Baltimore, and Washington, D.C.

For further information, contact
Professor Kat Wakabayashi
Department of Chemical Engineering
Bucknell University, Lewisburg, PA 17837
Phone 570-577-1114
kat.wakabayashi@bucknell.edu
http://www.bucknell.edu/graduatestudies

J. Csernica, Chair (PhD, M.I.T.)
Diffusion in polymers, polymer surface modification
M. D. Gross (PhD, Pennsylvania)
Electrochemistry and fuel cell, catalysis
E. L. Jablonski (PhD, Iowa Stte)
Thin films, surface chemistry
W. E. King (PhD, Pennsylvania)
Photodynamic therapy, hemodialysis
J. E. Maneval (PhD, U.C. Davis)
NMR methods, membrane and novel separations
M. J. Prince (PhD, U.C. Berkeley)
Environmental barriers, instructional design
T. M. Raymond (PhD, Carnegie Mellon)
Atmospheric science, organic aerosols, air pollution
R. C. Snyder (PhD, U.C. Santa Barbara)
Conceptual design, crystallization
W. J. Snyder (PhD, Penn State)
Polymer degradation, kinetics, drag reduction
M. A. S. Vigeant (PhD, Virginia)
Bacterial adhesions to surfaces
B. M. Vogel (PhD, Iowa State)
Biomaterials, polymer chemistry
K. Wakabayashi (PhD, Princeton)
Polymer hybrid materials, sustainable processing





BROWN UNIVERSITY

GRADUATE STUDY IN CHEMICAL AND BIOCHEMICAL ENGINEERING

Major Research Themes

- **Biochemical engineering** - microfluidics, biodetection, biosensors, biotransport processes, bioseparation processes, disease diagnostics, rheology, physiological fluid mechanics
- **Nanotechnology** – nanomaterials, nanotoxicology, biological, environmental, and energy applications
- **Environmental and energy technology:** electrochemical separations, fluid-particulate systems, heavy metals recovery/remediation, advanced adsorption/ adsorbents, VOCs, vapor infiltration, fuel cells

A program of graduate study in Chemical and Biochemical Engineering for the M.Sc. or Ph.D. degree

Teaching and Research Assistantships as well as Industrial and University fellowships are available

For further information, email:

Professor R.H. Hurt, Graduate Representative
Chemical and Biochemical Engineering Program
School of Engineering, Brown University, Providence, RI 02912
Robert_Hurt@brown.edu
Please visit - http://www.engin.brown.edu

Cleveland State University

M.S. Chemical Engineering
M.S. Biomedical Engineering
D.Eng. Chemical Engineering
D.Eng. Applied Biomedical Engineering
(in collaboration with The Cleveland Clinic, rated 4th best hospital in the U.S.A.)

Research opportunities include:

reaction engineering	biomaterials
process systems engineering	orthopaedics
thermodynamics	BioMEMS
materials processing	biomechanics
bioprocessing	cardiovascular devices
molecular simulations	cardiovascular imaging
metabolic modeling	biofluids

Research is conducted in state-of-the-art labs either at Cleveland State University or at The Cleveland Clinic. Assistantships are available for qualified applicants.

For more information contact:
Graduate Program Director, Chemical and Biomedical Engineering Department, Cleveland State University, 2121 Euclid Avenue, Stilwell Hall 455, Cleveland, OH 44115;
che@csuohio.edu
website: http://www.csuohio.edu/chemical_engineering/

University of Dayton

MS in Chemical Engineering, Bioengineering and Materials Engineering

PhD in Materials Engineering

Research areas:

- Agitation
- Biomaterials; Bioprocess Engineering
- Biosystems Engineering
- Composite Materials; Surface Sciences
- Fuel Cells
- Multifunctional Materials
- Nano Materials
- Petroleum Flow Assurance
- Polymer Science
- Process Modeling
- Thermal Management

We specialize in offering each student an individualized program of study and research with most projects involving pertinent interaction with industrial personnel

For additional information contact us:
Department of Chemical and Materials Engineering
University of Dayton, Dayton, Ohio
45469-0246 (937) 229-2627
Charles.Browning@notes.udayton.edu
www.udayton.edu/engineering/chemical_and_materials/index.php

UNIVERSITY of DAYTON

UNIVERSITY *of* NEW HAMPSHIRE

DEPARTMENT OF CHEMICAL ENGINEERING

At the M.S. and PhD levels, we offer research opportunities in biofuels, biomedical engineering, biochemical engineering, electrochemical engineering, reaction engineering, tissue engineering, energy and environmental engineering. All of our graduate students are fully supported by teaching or research assistantships. The chemical engineering department recently moved to a new building, which provides state of the art facilities for teaching and research.

For additional information please contact:
Department of Chemical Engineering
University of New Hampshire
Kingsbury Hall, W301
Durham, NH 03824-3591
Tel: 603-862-3654
Email:. CHE.Dept@unh.edu
Web: http://www.unh.edu/chemical-engineering
To obtain the graduate application or more information about the application process, visit the Graduate School website at http://www.gradschool.unh.edu