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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.<sup>1-4</sup> 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](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.<sup>5</sup> 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](http://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.

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## ***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. □

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

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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<sup>[1]</sup> 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.<sup>[2]</sup> and Young, et al.<sup>[3]</sup> 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<sup>[1]</sup> 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<sup>[4]</sup> 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

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**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.,<sup>[5]</sup> suggest that cross-course projects can be followed; Jimenez, et al.,<sup>[6]</sup> 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. Dorskocil<sup>[7]</sup> recommends combining the design of experiment techniques with a current experiment to present a more “real world” situation to the student. Felder and Brent<sup>[8]</sup> enthusiastically promote active learning. Based on the game show “Survivor,” Newel<sup>[9]</sup> 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,<sup>[10]</sup> Smith,<sup>[11]</sup> and Johnson and Johnson,<sup>[12]</sup> however, generic skills such as team management and time management should not be taught only during keynote 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](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.,<sup>[13]</sup> 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 Imai and Kaizen<sup>[14]</sup>).

#### **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,<sup>[15]</sup> 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 type-written 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<sup>[1]</sup> 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<sup>[16]</sup> 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<sup>[1]</sup> 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.

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**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

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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.<sup>[1]</sup> 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.<sup>[2]</sup> 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.<sup>[3]</sup> 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.<sup>[4,5]</sup> 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.<sup>[6]</sup> Some beverage companies have also begun using plastic bottles for these

reasons as well as for safety at beaches and public events.<sup>[7]</sup> The claim has been made that plastic bottles stay cold as long as glass and longer than aluminum.<sup>[8]</sup>

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.<sup>[9]</sup> Conversely, researchers at Loyolla College found that on heating in air, an aluminum bottle kept its contents colder slightly

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*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 $\rho$ (kg/m <sup>3</sup> )	Heat Capacity $C_p$ (J/kg K)	Thermal Conductivity $k$ (W/m K)	$k/t$ (W/m <sup>2</sup> 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	

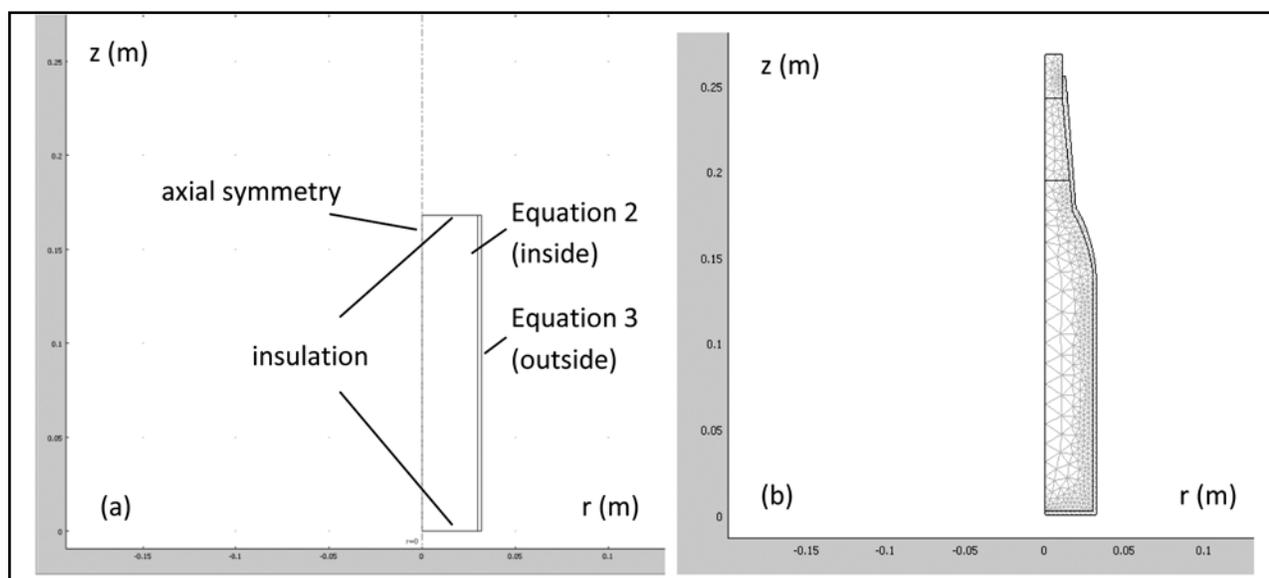
longer than a glass bottle but explained that the two bottles behaved essentially identically because the heat transfer is controlled by natural convection and radiation at the outer surface rather than conduction through the bottle wall in this situation.<sup>[10]</sup> Calculations they made indicated 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

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T \quad (1)$$

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

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

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

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

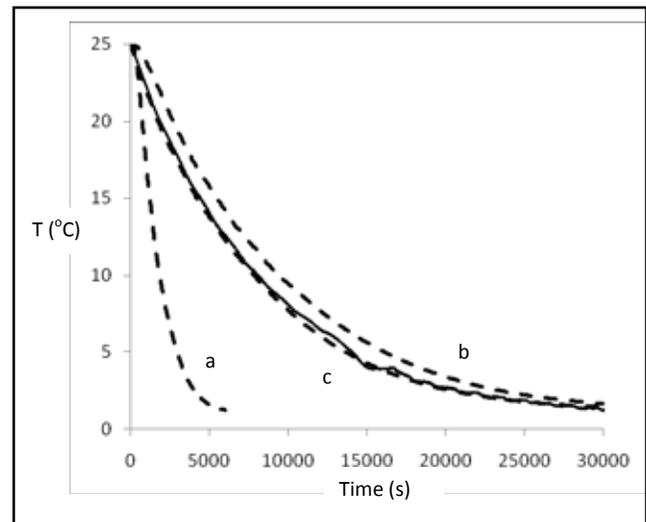
simple analysis explains the observed trends in our data sufficiently well. To provide a physical interpretation of the heat transfer coefficient, we have also developed models of our bottles that include an equivalent stagnant air or water layer at the outside surface of the bottle. Physical properties 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  $T_{\text{refrigerator}}$  (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  $T_o = 1$  °C; (b) outside heat transfer coefficient,  $h_o = 9$  W/m<sup>2</sup> 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/m<sup>2</sup> K and  $h_i = 400$  W/m<sup>2</sup> K to account for natural convection inside the bottle.

<b>TABLE 2</b>				
<b>Outside Heat Transfer Coefficients and Biot Numbers Upon Cooling in Refrigerator and Ice Water</b>				
	Cooling in refrigerator		Cooling in ice water	
	$h_o$ (W/m <sup>2</sup> K)	Bi	$h_o$ (W/m <sup>2</sup> K)	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  $T = T_{\text{refrigerator}}$  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  $T_{\text{refrigerator}}$ , 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  $T_{\text{surface}}$  to  $T_{\text{refrigerator}}$ , 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.<sup>[11]</sup> 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<sup>2</sup> 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<sup>2</sup> 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,

$$Bi = (h_o t) / k \quad (4)$$

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,  $\delta_e$ , 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  $T = T_{\text{refrigerator}}$ , but instead is given as the length required to match the observed heat transfer coefficient,

$$\delta_e = \frac{k}{h_o} \quad (5)$$

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<sup>2</sup> K. Including an air layer of this thickness in an equivalent conduction-only model with a fixed  $T = T_{\text{refrigerator}}$  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<sup>2</sup> 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.

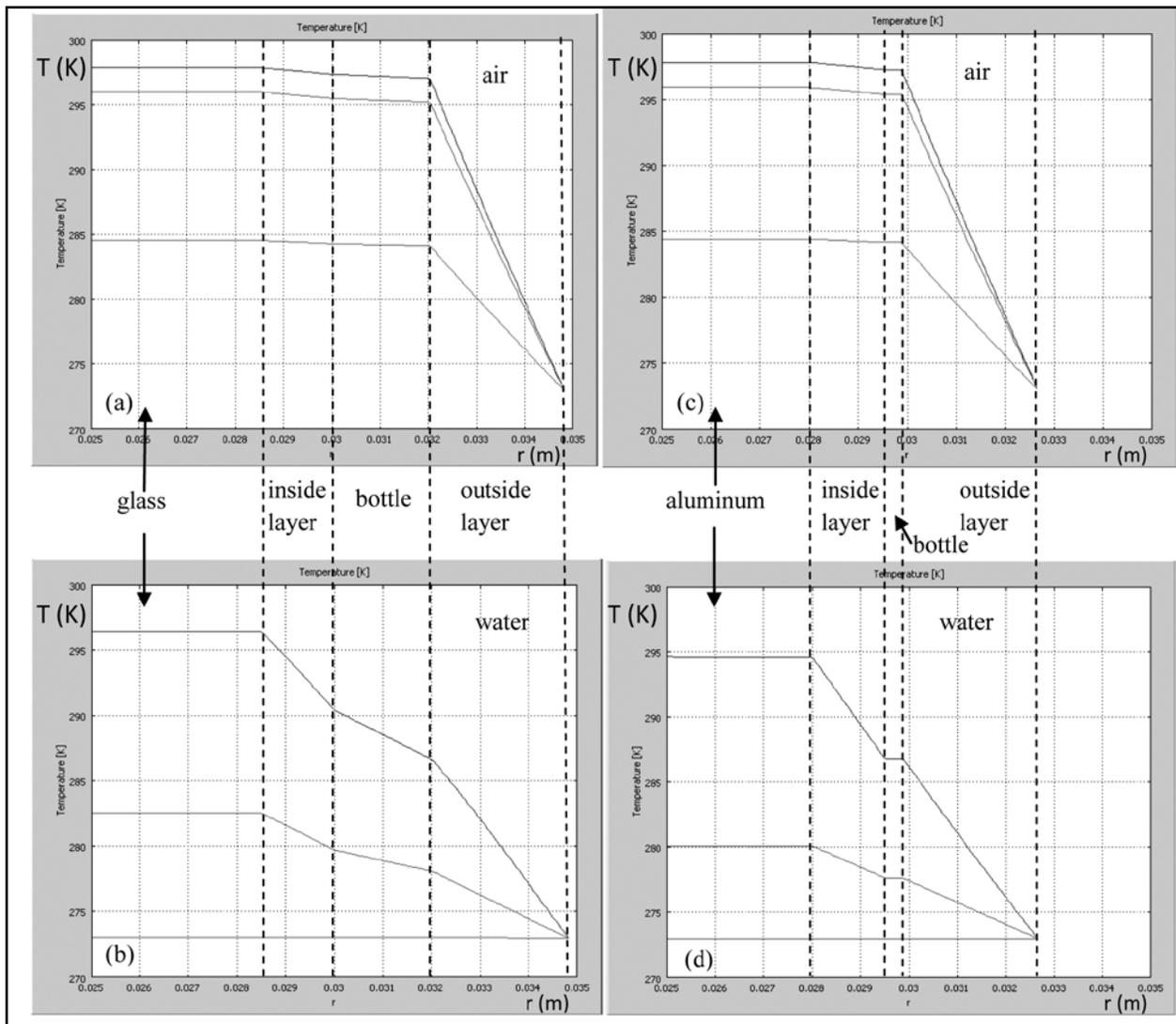
The heat transfer rate by conduction through a composite material is given by

$$q = \frac{\Delta T}{\sum R_j} \quad (6)$$

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

$$R_j = \frac{t_j}{k_j A_j} \quad (7)$$

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

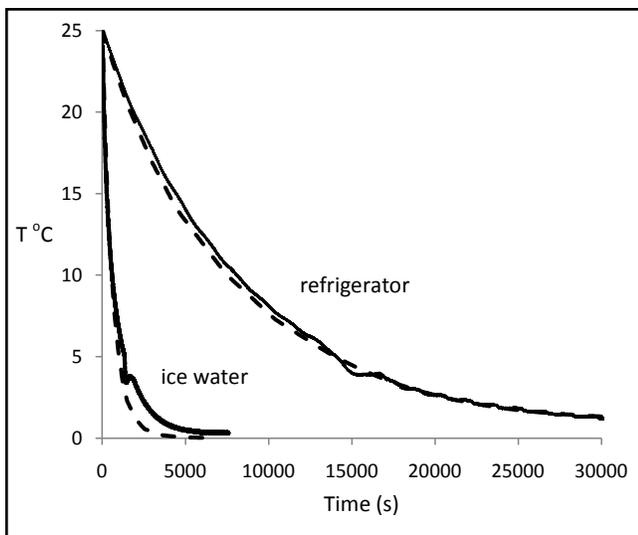


**Figure 3.** Predicted temperature profiles in the radial direction for our conduction-only model with effective outside thermal resistance layer of 0.00278 m and effective inside thermal resistance layer of 0.0015 m at three times (60, 600, and 6000 s) for cooling with outside  $T = 0$  °C and initial inside  $T = 25$  °C 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,

$$q = h_o A_o (T_o - T_a) \quad (8)$$

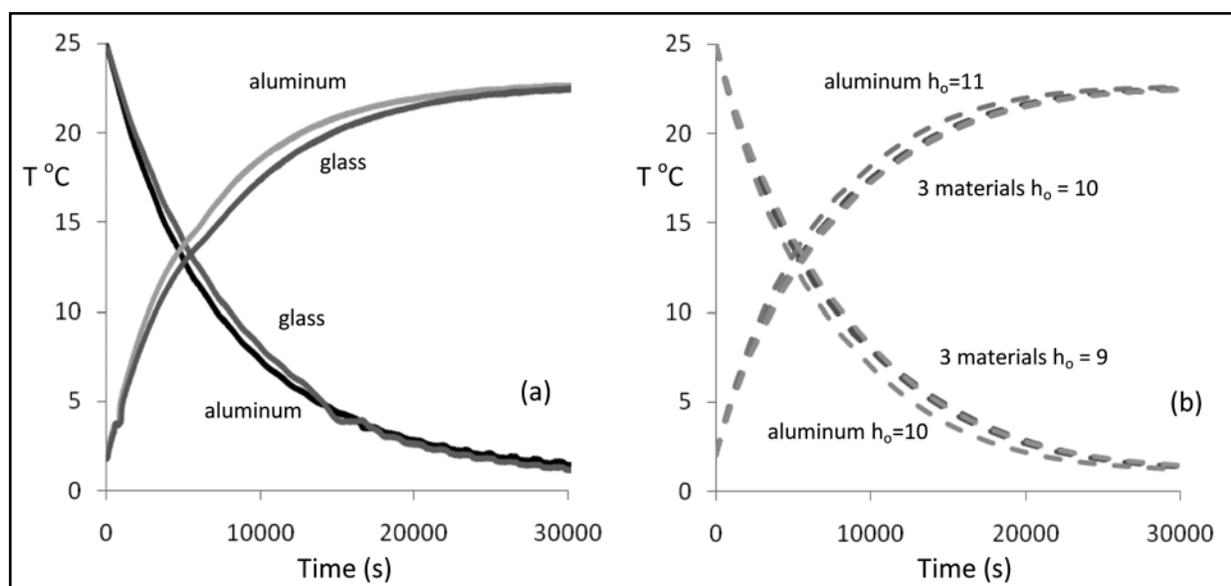
to evaluate the value of  $h_o$  represented by the air layer. For



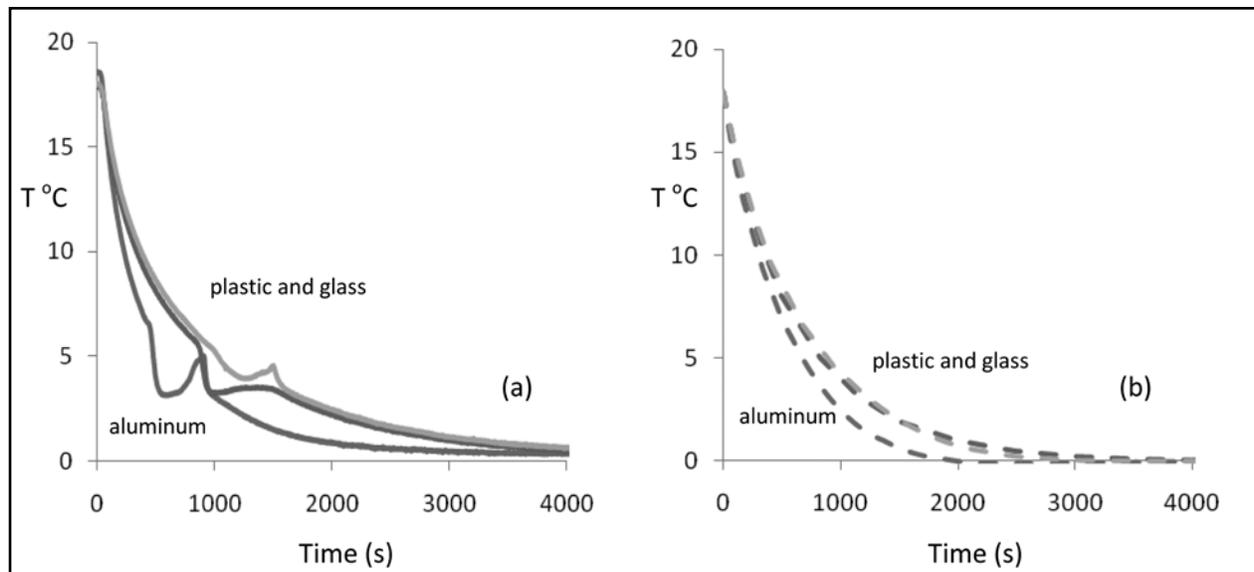
**Figure 4.** Comparison of cooling rates for glass bottle in refrigerator or ice water. Solid lines, experimental data. Dashed lines, equivalent stagnant layer conduction models.

example, at 60 s, the heat flow across the outside wall was 7.39985 W and  $\Delta T$  was approximately 23.35 K. Taking into account the bottle outside surface area of 0.03381 m<sup>2</sup> yields a value of  $h_o$  near 9 as expected.

*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  $h_i = 400 \text{ W/m}^2\text{K}$ ,  $h_o = 9 \text{ W/m}^2\text{K}$  ( $10 \text{ W/m}^2\text{K}$  for aluminum) on cooling and  $h_o = 10 \text{ W/m}^2\text{K}$  ( $11 \text{ W/m}^2\text{K}$  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  $h_o = 200 \text{ W/m}^2\text{K}$ ,  $h_i = 400 \text{ W/m}^2\text{K}$ .

*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  $4 \text{ }^\circ\text{C}$  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  $6 \text{ }^\circ\text{C}$ , for example.<sup>[12]</sup> 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  $18.5 \text{ }^\circ\text{C}$ , shown in Figure 6, it was about 5 minutes faster, but for a starting temperature of  $24 \text{ }^\circ\text{C}$  (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).

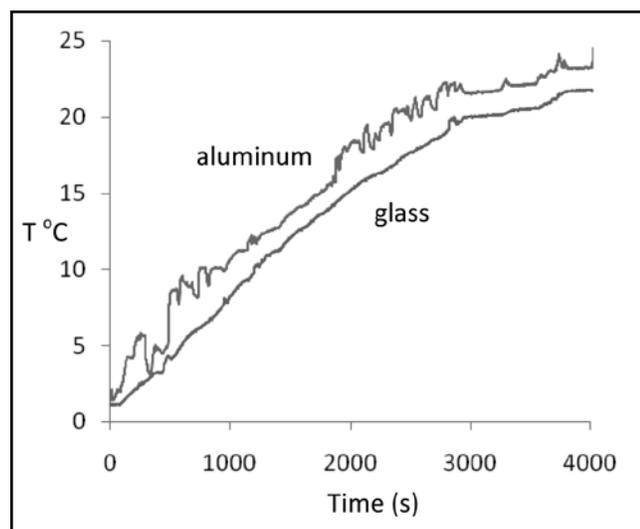
To give students a physical feel for the heat transfer process, we found it effective to fill an aluminum bottle and a glass bottle with ice water and have them hold each one. The aluminum bottle feels colder because it conducts heat away from the hand more readily. This explains why aluminum cools faster 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



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

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.

## ACKNOWLEDGMENTS

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## 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<sup>[13]</sup>

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

where

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

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

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

Pr, Gr, and Ra are the Prandtl, 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  $T_\infty = 1^\circ\text{C}$  given in Table A1, and an initial bottle surface temperature,  $T_s$ , of  $25^\circ\text{C}$ , the value of  $h_o$  given by Eq. (A1) is  $4.98\text{ W/m}^2\text{K}$ .

*Radiative heat transfer coefficient – cooling in refrigerator.* The radiation heat transfer coefficient can be estimated by<sup>[14]</sup>

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

Using an emissivity,  $\varepsilon$ , for glass of 0.93 and Boltzmann constant,  $\sigma$ , of  $5.67 \times 10^{-8}\text{ W/(m}^2\text{K}^4)$  yields a value of  $h_r = 4.94\text{ W/m}^2\text{K}$ .

*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  $h_o = 4.98 + 4.94 = 9.92\text{ W/m}^2\text{K}$ . Since this value will decrease with time an average value of  $9\text{ W/m}^2\text{K}$  seems reasonable.

*Outside convective heat transfer coefficient – cooling in ice water.* Using the values for water at  $0^\circ\text{C}$ , given in Table A1 yields an outside heat transfer coefficient for water via Eq. (A1) of  $h_o = 304\text{ W/m}^2\text{K}$ . The presence of crushed ice in the water near the bottle and the fact that the volume expansivity,  $\beta$ , goes from negative to positive and equals zero at  $4^\circ\text{C}$ , 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  $200\text{ W/m}^2\text{K}$  is not unreasonable.

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

$$h_i = \frac{k}{H} [0.55Ra^{0.25}] \quad (A6)$$

Using the properties of water at  $25^\circ\text{C}$  shown in Table A1,  $T_\infty = 25^\circ\text{C}$ , and  $T_s = 1^\circ\text{C}$  in this equation yields  $h_i = 422\text{ W/m}^2\text{K}$  in agreement with the fitted average value of  $400\text{ W/m}^2\text{K}$  that we used.  $\square$

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

# DRUG TRANSPORT AND PHARMACOKINETICS

## *For Chemical Engineers*

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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.<sup>[1]</sup> 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.<sup>[2]</sup> 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.<sup>[3]</sup> Cavanagh

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and Wagner<sup>[4]</sup> 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 pharmaceutical distributes to rapidly perfused tissues<sup>[5]</sup> 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*):<sup>[5]</sup>

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

or

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

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:

$$C_p = C_p^0 e^{-k_{el} \times t} \quad (3)$$

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

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

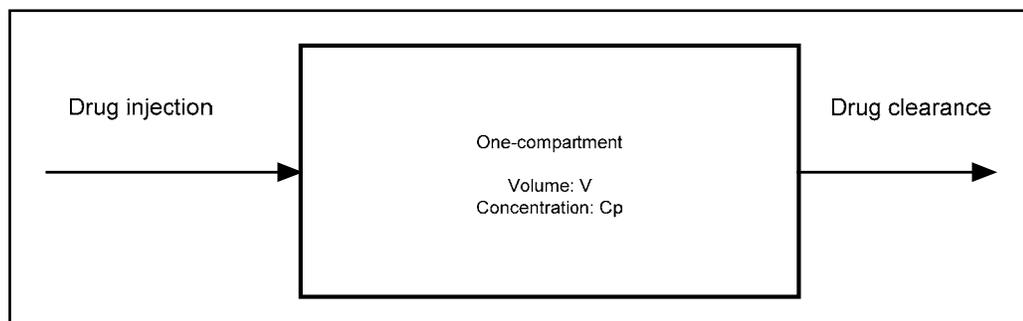
It can be shown that the time required for the plasma drug to drop to one-half of its initial value is:

$$t_{1/2} = \frac{0.693}{k_{el}} \quad (5)$$

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  $\tau$ :

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



**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  $n$ th interval is:<sup>[1]</sup>

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

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

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

and

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

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  $\text{KMnO}_4$  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  $\text{KMnO}_4$  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.

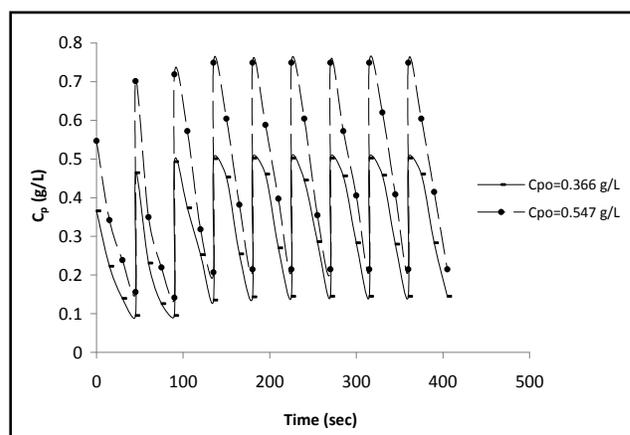


Figure 3. Concentration of  $\text{KMnO}_4$  in the central compartment using nine IV boluses and two separate drug sizes:  $k_{el} = 0.028 \text{ sec}^{-1}$ , and  $\tau = 45 \text{ sec}$ ,  $C_p^0 = 0.366 \text{ g/L}$  (regimen 1) and  $C_p^0 = 0.547 \text{ g/L}$  (regimen 2).

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,<sup>[1]</sup> 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*):

$$\frac{dVC_p}{dt} = k_0 - k_{el} VC_p \quad (10)$$

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

$$C_p(t) = \frac{k_0}{k_{el} V} (1 - e^{-k_{el} t}) \quad (11)$$

The steady-state concentration:

$$C_{pss} = \frac{k_0}{k_{el} V} \quad (12)$$

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:

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

where  $\tau$  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:

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

### 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.*,  $k_{el}=0.014 \text{ min}^{-1}$ ,  $C_{pss}=2.0 \text{ g/mL}$ ,  $k_0=5.6 \text{ g/min}$ ). 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.

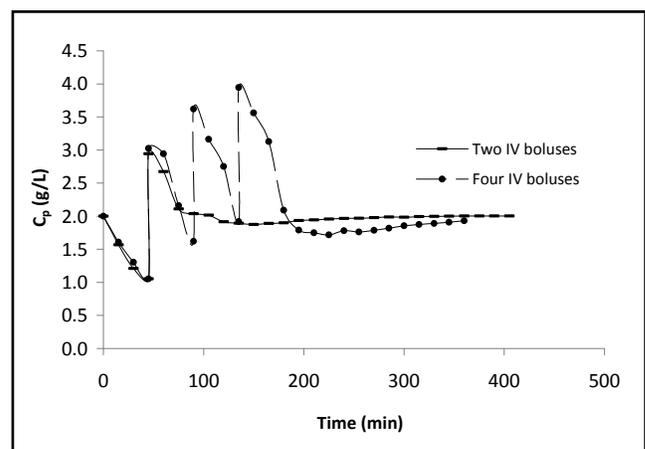
### Results and Discussions

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.<sup>[6]</sup> 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  $k_0 = 5.6 \text{ g/min}$ .

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.

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# INTRODUCING DECISION MAKING UNDER UNCERTAINTY AND STRATEGIC CONSIDERATIONS IN ENGINEERING DESIGN

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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.<sup>[1]</sup> 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<sup>[2]</sup>) or the rolling

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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

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

where  $N$  is the number of possible outcomes,  $P_i$  is the probability that outcome  $i$  will occur, and  $\pi_i$  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.

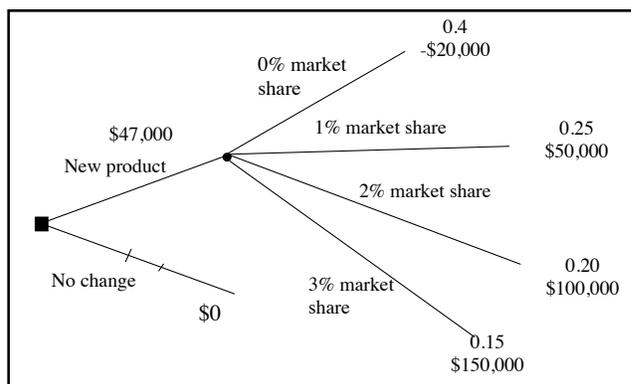
An example like this introduces students to a methodology for taking uncertainty into account, and provides the opportunity to discuss decision tree analysis (see Reference 2, or any other managerial economics textbook, for more on decision trees). The discussion of expected profit, however, also leads 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.<sup>[2]</sup> 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  $\pi$  between the two extreme values  $\pi_{\min}$  and  $\pi_{\max}$  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  $\pi$ . In particular:

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

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  $\pi$  and a gamble with probability P of a return  $\pi_{\min}$  and probability (1 - P) of a return  $\pi_{\max}$ . 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

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

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

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.

**Game 1:** 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

**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  $U(0)$ .

	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

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:

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

Option 2: 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

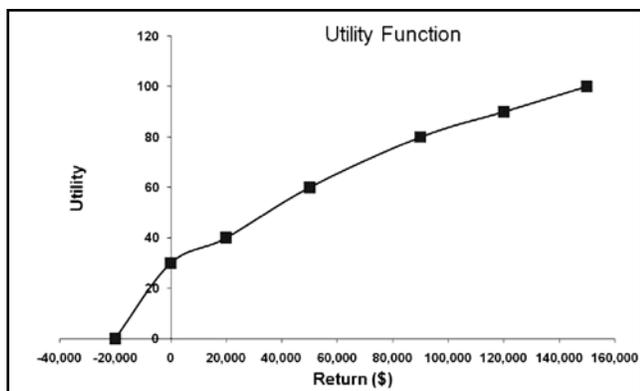
Option 1: If the die comes up 1, 2, you win \$150,000, but if it comes up 3,..., 10 you lose 20,000.

Option 2: 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).”



**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  $\text{CO}_2$  emission by 15%. For the past few years, Independent Chemical, Inc., has subcontracted another company to process  $\text{CO}_2$ . The cost keeps rising, however, and Independent Chemical, Inc., is considering handling the  $\text{CO}_2$  capturing in-house. Your consulting company is hired by Independent Chemicals, Inc. They want you to suggest which of the following technology options for  $\text{CO}_2$  sequestration they should use:

Option 1: Build a bio-energy carbon storage plant next to their existing facility to capture and store  $\text{CO}_2$ .

Option 2: Use gas hydrate technology to transport  $\text{CO}_2$  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).

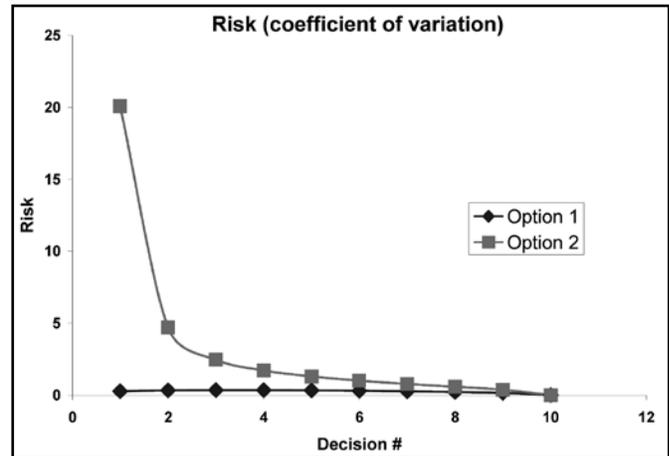
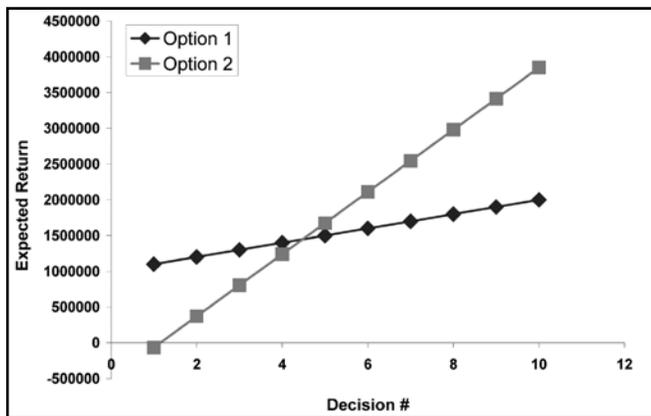
- Continue making choices up to the tenth set of options having in mind that as you go down the list the probability of the most favorable outcome in both options increases by 1/10.

**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	

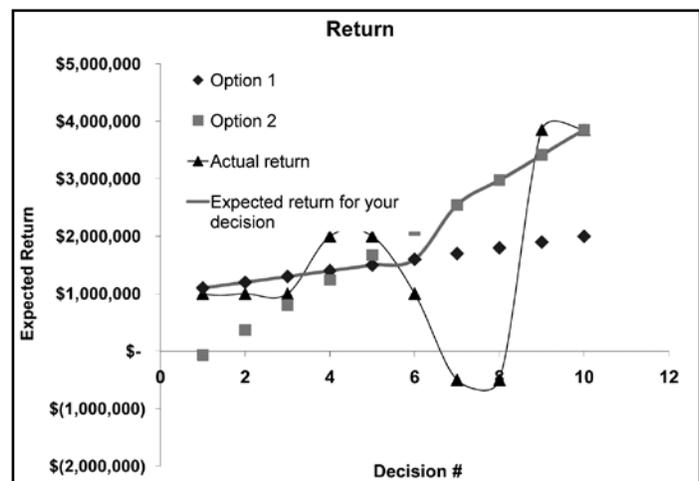
**Figure 4.** Example of the game that students play in order to determine their attitude towards risk. Option 1 is a gamble that has a smaller risk, but it also has a smaller expected profit beyond the fifth row.



**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.,<sup>[3]</sup> 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 through 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<sup>[4]</sup> or through the EconPort portal developed by J. Cox, et al., at Georgia State University.<sup>[5]</sup>

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.<sup>[1]</sup> 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,<sup>[2]</sup> where the cash flows are substituted by their certainty equivalent values.

## ACKNOWLEDGMENTS

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# VERSATILE DESKTOP EXPERIMENT MODULE (DEMO) ON HEAT TRANSFER

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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*.<sup>[1]</sup> It should be noted that this work was first presented and published in the 2009 ASEE conference proceedings as paper # AC 2009-1609.<sup>[2]</sup>

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  $\Delta$  changes such as  $\Delta T$ ,
- 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.<sup>[3-5]</sup> Other chemical engineering programs have adopted these experiments.<sup>[6]</sup> Since these hands-on ex-

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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 choose 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.<sup>[5]</sup>

## 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 Thermal-take 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.<sup>[1,7]</sup>

### Experimental Procedure:

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.*

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.

$$T(0) = T_{w,s} \Rightarrow T(0) = 122 \text{ °C} \quad (3)$$

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

The particular solution is in symbolic and numeric form:

$$T(x) = \frac{T_{p,s} - T_{w,s}}{L} x + T_{w,s}$$
$$T_{\text{polycarb}}(x) = \left( -3320 \frac{\text{°C}}{\text{m}} \right) x + 122 \text{ °C} \quad (5)$$

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.

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

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.

$$q_x'' = \frac{0.21 \frac{\text{W}}{\text{m} \cdot \text{K}}}{0.01\text{m}} (122 \text{ °C} - 88.8 \text{ °C}) = 697 \frac{\text{W}}{\text{m}^2} \quad (7)$$

### 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.

$$q_{x,\text{compound}}'' = \frac{0.21 \frac{\text{W}}{\text{m} \cdot \text{K}}}{0.01\text{m}} (122 \text{ °C} - 93.1 \text{ °C}) = 607 \frac{\text{W}}{\text{m}^2} \quad (8)$$

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

$$R_{t,c}'' = \frac{122 \text{ °C} - 88.8 \text{ °C}}{697 \frac{\text{W}}{\text{m}^2}} = 0.04763 \frac{\text{°C} \cdot \text{m}^2}{\text{W}} \quad (9a)$$

$$R_{t,c,\text{compound}}'' = \frac{122 \text{ °C} - 93.1 \text{ °C}}{607 \frac{\text{W}}{\text{m}^2}} = 0.04761 \frac{\text{°C} \cdot \text{m}^2}{\text{W}} \quad (9b)$$

$$R_{t,c}'' - R_{t,c,\text{compound}}'' = 0.04763 \frac{\text{°C} \cdot \text{m}^2}{\text{W}} - 0.04761 \frac{\text{°C} \cdot \text{m}^2}{\text{W}} = 2.15 \times 10^{-5} \frac{\text{°C} \cdot \text{m}^2}{\text{W}} \quad (10)$$

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.

$$T(t)0 = 22.3\text{ °C} = 0 + C_1 \Rightarrow C_1 = 22.3\text{ °C} \tag{13}$$

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.

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

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

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

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  $\left(\frac{\text{W}}{\text{m}^3}\right)$ , 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

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

**Energy Balance at the Mug Warmer Surface:**

Energy generated in the plate = energy convected away from plate

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

While convective heat transfer coefficients can be determined more rigorously, for this exercise, it is fine to use  $h = 5 \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$ . The thickness of the mug warmer’s heating coil has to be assumed from the thickness of the unit in use, but  $L=0.01\text{m}$  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:

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

Heat flux is then:

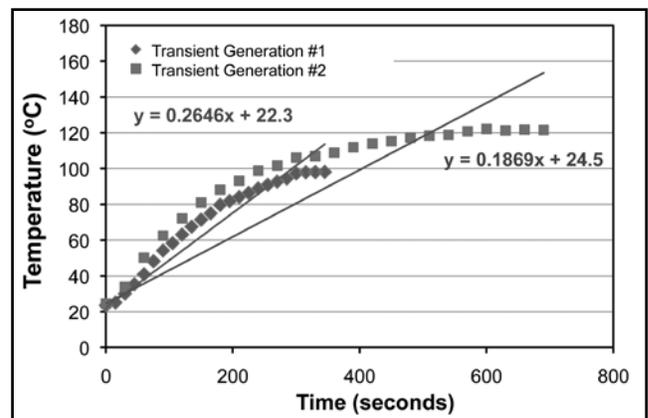
$$q'' = \dot{q} L = 50,000 \frac{\text{W}}{\text{m}^3} \cdot 0.01\text{m} = 500 \frac{\text{W}}{\text{m}^2} \tag{19}$$

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

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

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

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



**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:

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

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

### Thermal Contact Resistance

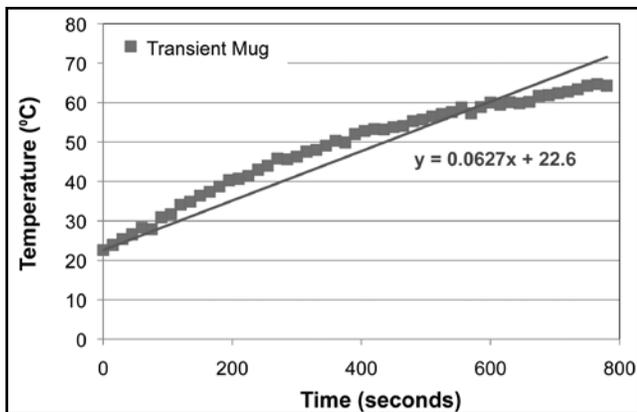
Thermal contact resistance can also be illustrated using a coffee mug on the plate warmer. By adding an empty cup at room temperature to the fully heated plate warmer, the students can observe the transient heating of the cup. If transient heating has already been covered, however, it is possible to 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.

#### Experimental Procedure:

1. Allow the plate warmer to heat up and reach steady-state (about 15 minutes to  $T_{ss} \approx 120^\circ\text{C}$ ).
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.

#### Analysis:

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



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

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  $\text{W}/\text{mK}$ .<sup>[1]</sup> 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):

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

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

$$q_x'' = \frac{T_{w,s} - T_{m,s}}{\frac{L_m}{k_m} + R_{t,c}''} = \frac{122^\circ\text{C} - 75^\circ\text{C}}{0.029 \frac{\text{m}^2\text{K}}{\text{W}} + R_{t,c}''} = 500 \frac{\text{W}}{\text{m}^2}$$

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

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  $\approx 12^\circ\text{C}$  at steady-state. As demonstrated in Figure 2, the inside surface of the coffee mug remains below  $70^\circ\text{C}$ . 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.<sup>[1]</sup>

#### Experimental Procedure:

1. Allow the plate warmer to heat up and reach steady-state (about 15 minutes to reach  $T_{ss} \approx 120^\circ\text{C}$ ).
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.

#### Analysis:

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-

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:

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

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  $M = (T_{w,s} - T_{\infty, \text{ambient}}) \sqrt{hp k A_c}$  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.<sup>[8]</sup>

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.<sup>[9]</sup>

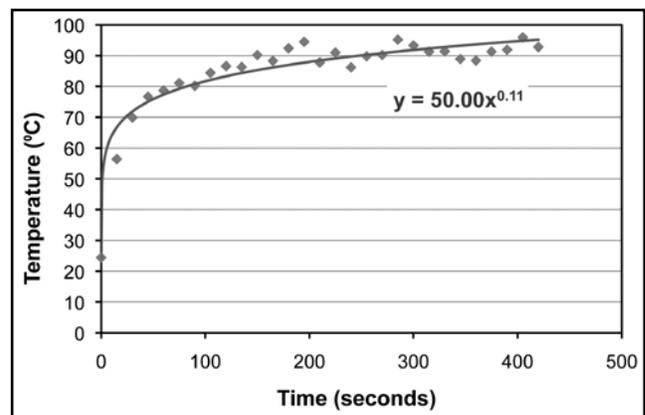
### CONCLUSIONS

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.

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**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.

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

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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.”<sup>[1]</sup> 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.<sup>[1]</sup> 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.<sup>[2]</sup> Continuing on this course will lead to fewer engineers with high-quality skills available to lead innovation in the United States.<sup>[1]</sup>

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,<sup>[3]</sup> the United States is still projected to face a shortage of up to 70,000 engineers in this decade.<sup>[1,4]</sup> 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.”<sup>[5]</sup> 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.

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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.<sup>[5]</sup> 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.

## 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

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 in 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	
<b>Creativity (Q1)</b>	
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
<b>Scientific Thought (Q2)</b>	
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
<b>Thoroughness (Q3)</b>	
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.

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).<sup>[2]</sup> 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.

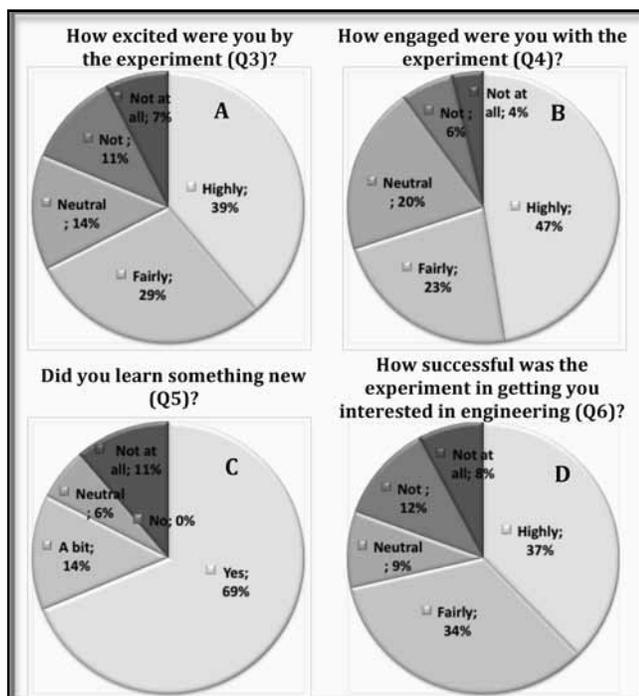
## ASSESSMENT

**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.

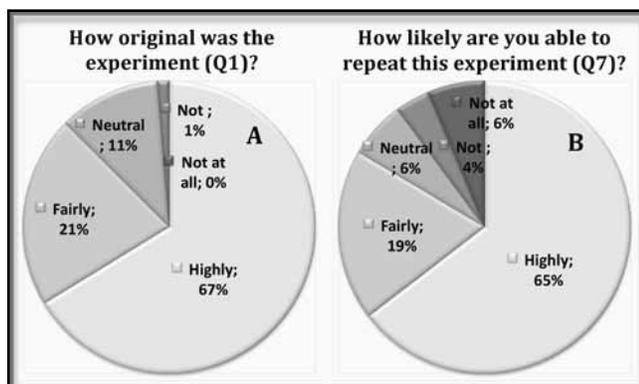
The judging process required that each HSS fill out a survey immediately after each demo viewed to ensure an accurate representation of their opinions. Four key questions were used on the HSS survey (Q3 - Q6 in Figure 1A) to gauge how successful a group's demo was at introducing and engaging

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.



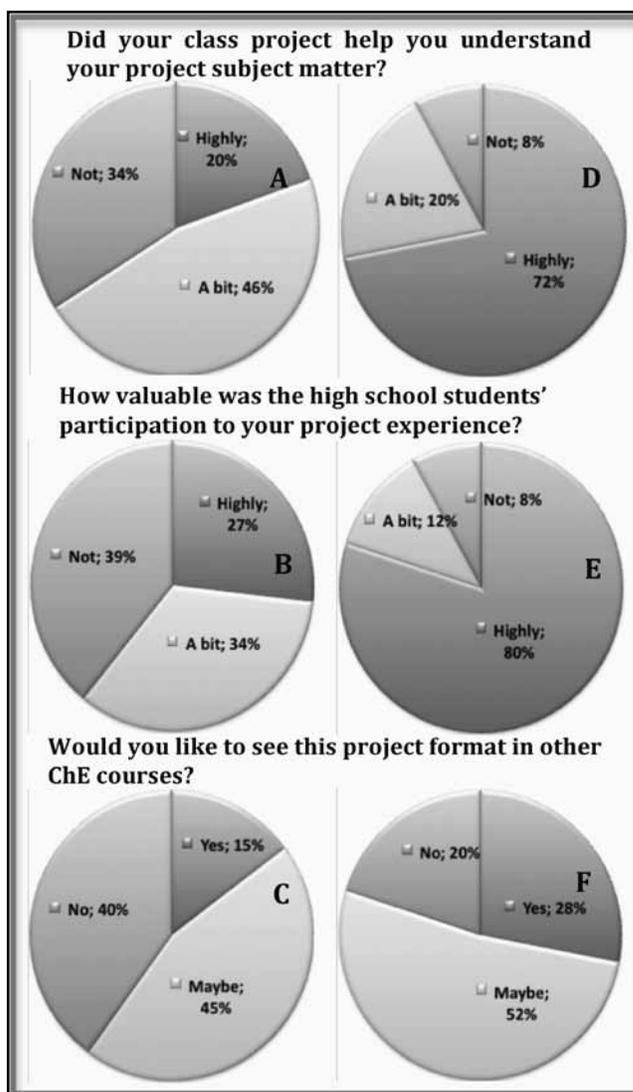
**Figure 2.** Summary of high school student survey on excitement and engagement rated on a scale of 1–10. Highly (Yes) = 9–10; Fairly (A bit) = 7–8; Neutral = 5–6; Not (No) = 3–4; Not at all = 1–2.



**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

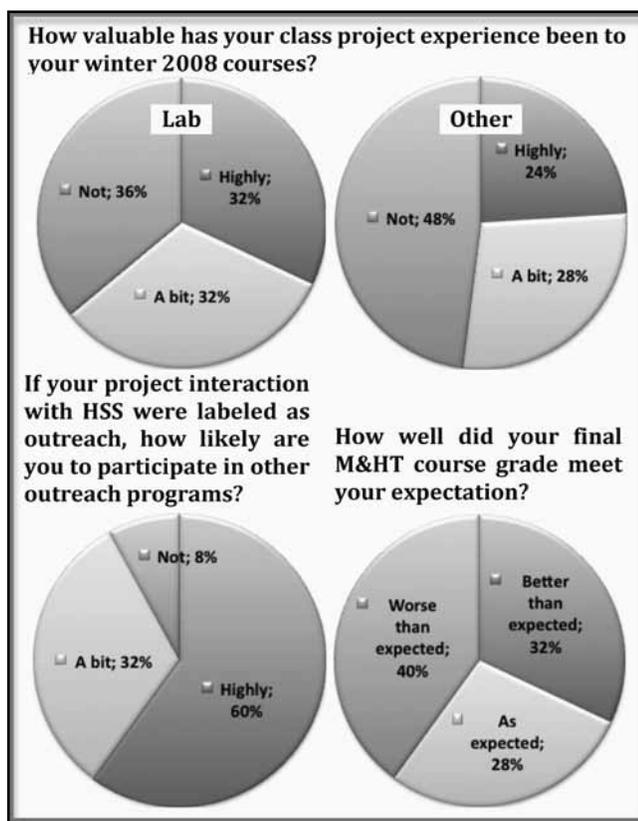
were currently enrolled in the junior ChE lab course, and 32% of these students indicated that their M&HT project experience was “highly” valuable to their winter lab course (Figure 5). Only 24% of all post-survey respondents, however, indicated that their ChE project experience was “highly” valuable 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

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,<sup>[6]</sup> 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,<sup>[7,8]</sup> 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 simultane-



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

ously 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<sup>[8]</sup> 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.

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**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, <i>e.g.</i> , 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?”

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**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 Snavelly wouldn’t be that tricky...now look at this problem here...”

\* \* \*

These three students illustrate three different *approaches to learning*.<sup>1</sup>

- 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.<sup>1</sup>

- *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. □

<sup>1</sup> 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](http://www.ncsu.edu/felder-public/Papers/Understanding_Differences.pdf)>

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## *Design Project on*

# CONTROLLED-RELEASE DRUG DELIVERY DEVICES:

## *Implementation, Management, and Learning Experiences*

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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.<sup>[1]</sup> 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.<sup>[2]</sup> Undeniably, many successful controlled-release drug delivery devices have been developed as a result of an almost arbitrary selection of components, configurations, and geometries.<sup>[2]</sup>

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This paper describes the introduction of a drug delivery project in a mass transfer course. Farrell and Hesketh<sup>[3]</sup> 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,<sup>[4]</sup> ii) cooling of a cup of coffee,<sup>[5]</sup> iii) cooking of potatoes,<sup>[6, 7]</sup> iv) drying of a bath towel,<sup>[8]</sup> and v) microwave drying.<sup>[9]</sup> Mass transfer phenomenon may also be illustrated via simple experiments to determine liquid<sup>[10]</sup> or vapor<sup>[11-13]</sup> diffusion coefficients, or via complex equipment to evaluate oxygen transfer in a bioreactor<sup>[14]</sup> or diffusion across a membrane.<sup>[15, 16]</sup>

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<sup>®</sup> 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.<sup>[17-22]</sup>

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<sup>®</sup>. 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<sup>3</sup>.*

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

Fabrication Technique	Description	Reference
Emulsion-based methods	<ul style="list-style-type: none"> <li>• These methods involve solvent extraction or evaporation from the emulsion containing the polymer.</li> <li>• The emulsion consists of the dispersed organic phase (polymer solution) and the continuous phase (usually an aqueous phase).</li> </ul>	[17]
Nanoprecipitation	<ul style="list-style-type: none"> <li>• 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.</li> </ul>	[18]
Spray-freezing into liquid	<ul style="list-style-type: none"> <li>• It is a novel cryogenic atomization technology for forming drug-encapsulated microparticles.</li> <li>• It involves spraying the liquid formulation directly into the cryogenic liquid, which results in rapid freezing of the atomized droplets and formation of microparticles.</li> <li>• The frozen particles are collected and lyophilized.</li> </ul>	[19]
Spray drying	<ul style="list-style-type: none"> <li>• The drug is dissolved or dispersed in an organic solution of the polymer which is then nebulized in a hot-air flow.</li> <li>• The solvent is evaporated and dried microparticles are recovered.</li> </ul>	[20]
Electro-hydrodynamic atomization (EHDA)	<ul style="list-style-type: none"> <li>• It is suitable for the preparation of nearly monodispersed microparticles from a solution, containing dissolved polymer and drug, by using an applied electric field.</li> </ul>	[21]
Supercritical anti-solvent (SAS)	<ul style="list-style-type: none"> <li>• The drug is dissolved in an organic solvent and the solution is injected into supercritical carbon dioxide.</li> <li>• The supercritical fluid, due to its high diffusivity, rapidly extracts the solvent and results in precipitating the microparticles.</li> </ul>	[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  $\mu\text{m}$ , ii) a cylindrical tablet with a radius of 3  $\mu\text{m}$  and a height of 6  $\mu\text{m}$ , iii) a cylindrical fiber with a radius of 3  $\mu\text{m}$ , and iv) a rectangular cuboid with a length, width, and height of 6, 6, and 7  $\mu\text{m}$ , respectively. The following tasks are assigned:

- Plot the drug-release profile for a duration of one week for the different geometries.
- Determine the geometries appropriate for this particular application.
- Plot the drug concentration profile for the different geometries at a time of i) one week, ii) two weeks, and iii) four weeks.
- 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  $\mu\text{m}$  and height 2  $\mu\text{m}$  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  $\text{mg}/\text{cm}^3$ . 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:

- Determine the diffusion coefficient of the drug in polymer 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:

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

Initial condition:  $C=C_0=30 \text{ mg}/\text{cm}^3$

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.<sup>[23, 24]</sup> 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  $2.50 \times 10^{-15} \text{ cm}^2/\text{s}$  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

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  $n$ th root of the first kind Bessel function of order zero;  $M_t$  is the amount of drug released in time  $t$ ;  $M_\infty$  is the amount of drug released after infinite time.

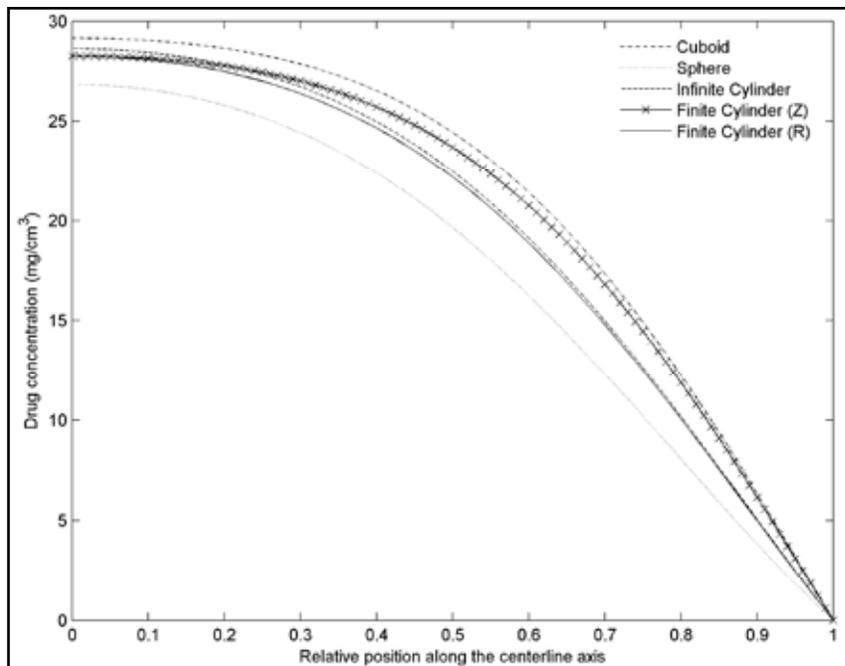
Geometry	Drug Concentration	Drug Release
Sphere (radius = $R$ )	$\frac{C - C_s}{C_0 - C_s} = -\frac{2R}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin\left(\frac{n\pi r}{R}\right) \exp\left(-\frac{n^2 \pi^2 Dt}{R^2}\right)$	$\frac{M_t}{M_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \pi^2 Dt}{R^2}\right)$
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 = $2c$ )	$\frac{C - C_s}{C_0 - C_s} = \frac{64}{\pi^3} \sum_{m=0}^{\infty} \frac{(-1)^m}{2m+1} \cos\left[\frac{(2m+1)\pi x}{2a}\right] \exp\left[-\frac{(2m+1)^2 \pi^2 Dt}{4a^2}\right]$ $\times \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cos\left[\frac{(2n+1)\pi y}{2b}\right] \exp\left[-\frac{(2n+1)^2 \pi^2 Dt}{4b^2}\right]$ $\times \sum_{p=0}^{\infty} \frac{(-1)^p}{2p+1} \cos\left[\frac{(2p+1)\pi z}{2c}\right] \exp\left[-\frac{(2p+1)^2 \pi^2 Dt}{4c^2}\right]$	$\frac{M_t}{M_\infty} = 1 - \frac{512}{\pi^6} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{p=0}^{\infty} \frac{1}{(2m+1)^2} \exp\left[-\frac{(2m+1)^2 \pi^2 Dt}{4a^2}\right]$ $\times \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2 \pi^2 Dt}{4b^2}\right]$ $\times \sum_{p=0}^{\infty} \frac{1}{(2p+1)^2} \exp\left[-\frac{(2p+1)^2 \pi^2 Dt}{4c^2}\right]$

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.

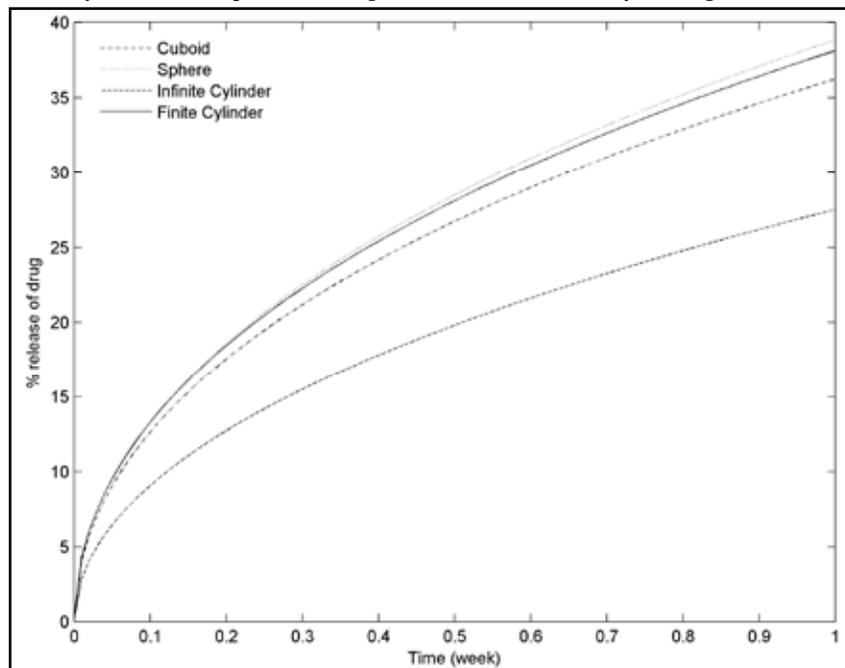
In the next part of the question, given the information that 40% of the same drug is released to the body within one week, we need to find the diffusion coefficient of the drug in polymer B. Since it was not possible to rewrite the expression for the drug release equation explicitly to solve for the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

## 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.



**Figure 1.** Drug-concentration profiles based on diffusion coefficient of  $2.50 \times 10^{-15} \text{ cm}^2/\text{s}$  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  $2.50 \times 10^{-15} \text{ cm}^2/\text{s}$  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  $0.667 \mu\text{m}^{-1}$ , respectively. The corresponding percentages of drug released after 1 week are 38.8, 38.1, 36.2, and 27.5%, respectively.

### **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.

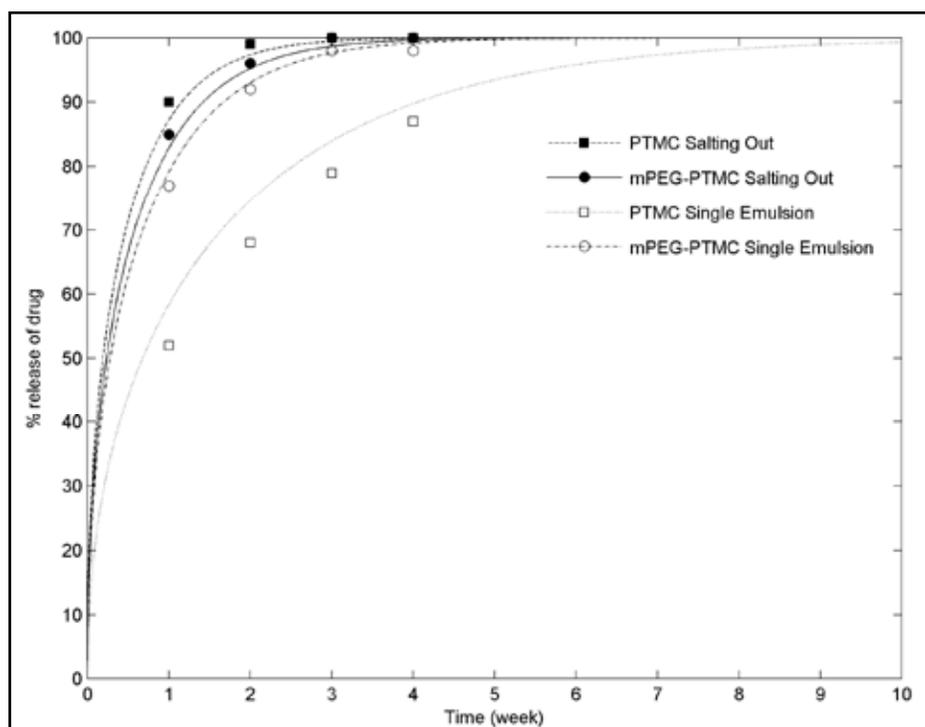
For the second section, the reports were graded based on the ability to explain the methodology and justify the assumptions and the choice of equations, the accuracy of the solutions, and the discussion of the simulation results. A good discussion should include explanations for the differences in drug 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.<sup>[25]</sup> The profiles are obtained based on a diffusion coefficient of 22.6, 4.8, 12.7, and  $4.8 \times 10^{-18}$  cm<sup>2</sup>/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

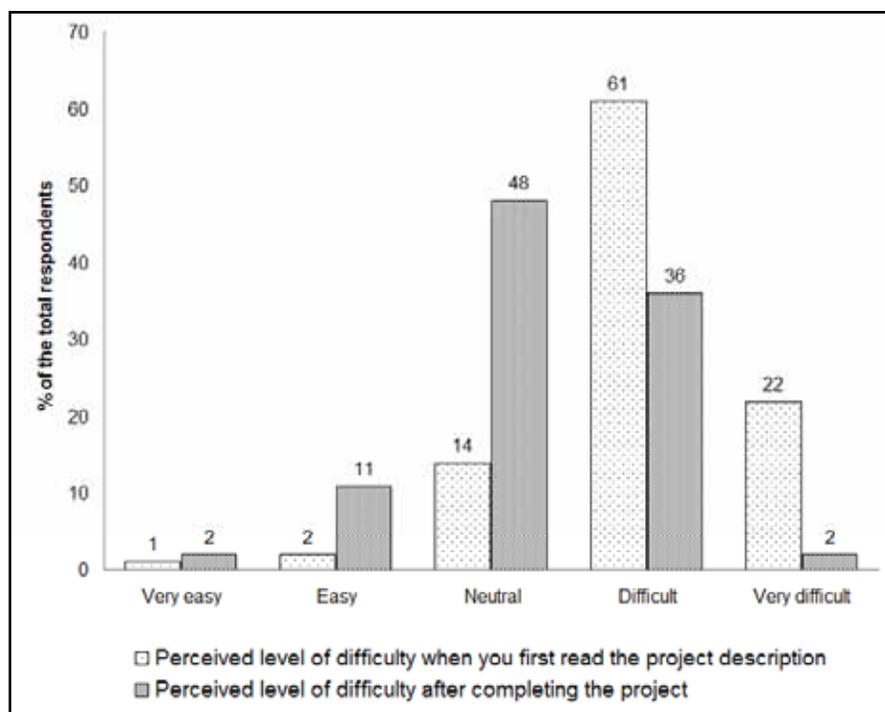
the earlier two sections of the project, a handful of teams had simply discussed the fabrication techniques without considering the drugs they had been assigned.

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).

## 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



**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.

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 up-front of the weightage of the individual components.

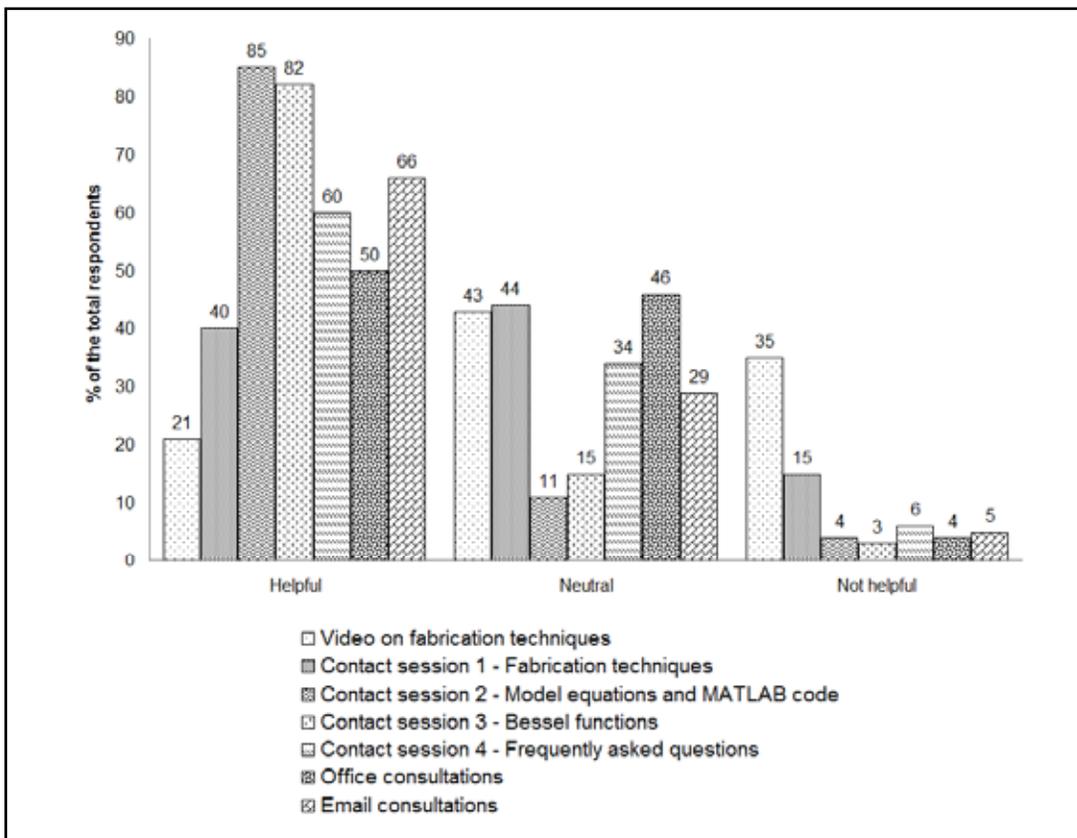
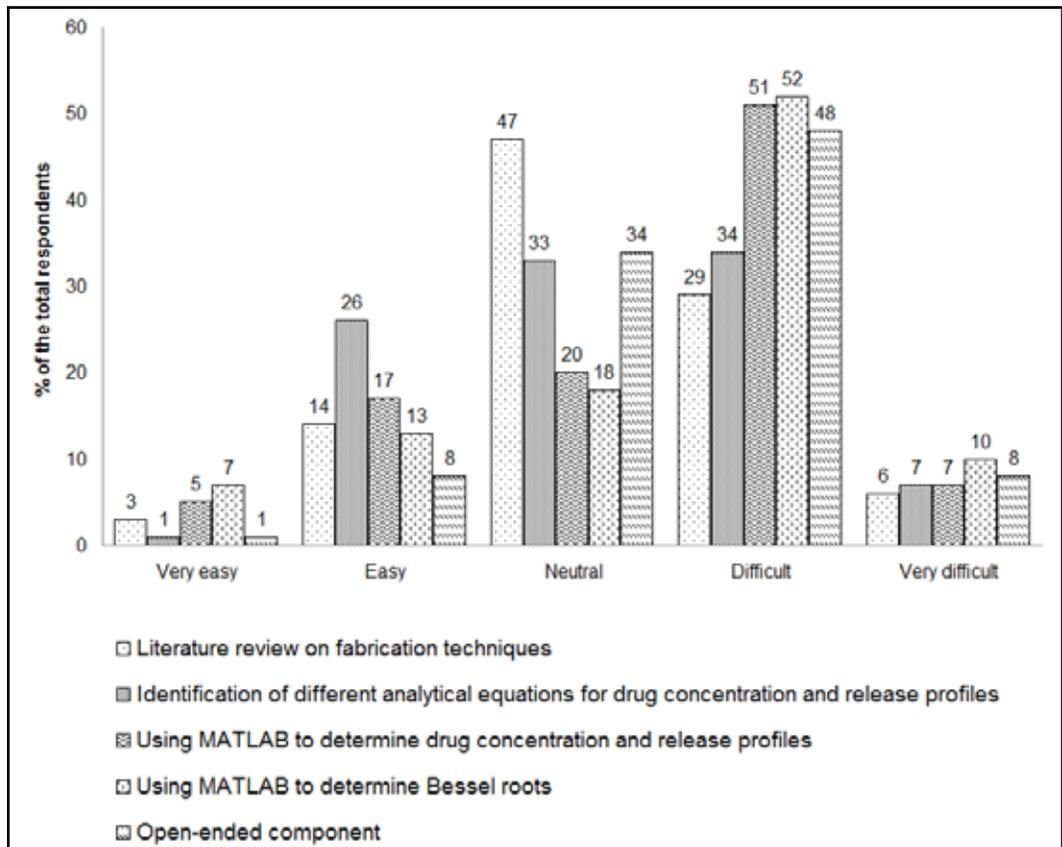
## CONCLUSION

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.

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# AN UNDERGRADUATE COURSE IN MODELING AND SIMULATION OF MULTIPHYSICS SYSTEMS

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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,<sup>[1-5]</sup> 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.<sup>[1,6]</sup> 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.

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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.<sup>[7,8]</sup> 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.,<sup>[1]</sup> and Tosun<sup>[3]</sup> 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<sup>[9]</sup> and Chadrupatla and Belegundu.<sup>[10]</sup>

- 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,<sup>[6]</sup> Bird, et al.,<sup>[11]</sup> Tosun,<sup>[3]</sup> and the COMSOL library.<sup>[11]</sup>
- 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,<sup>[11]</sup> Zimmerman,<sup>[6]</sup> and Hung, et al.<sup>[7]</sup>

## 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 of 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 sub-

mitted 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.<sup>[6]</sup> 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.*<sup>[12,13]</sup>). The drug is placed into a drug reservoir, assumed to be a solid sphere of radius  $\delta$ , 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

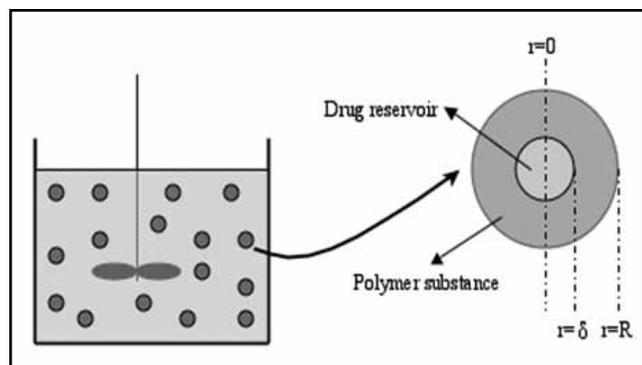


Figure 1. Physical system.

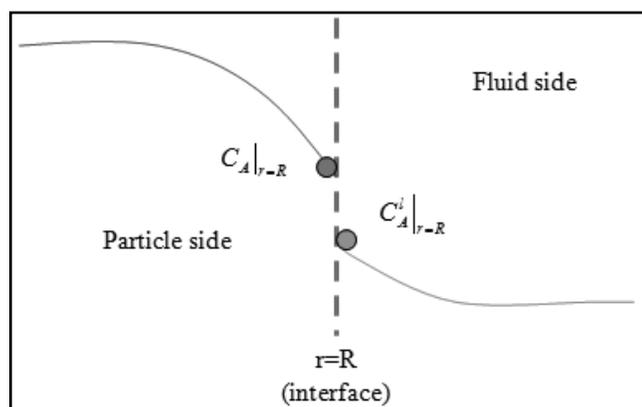


Figure 2. Coupling of the macro and the nano systems.

nano-particles,  $N_p$ . 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.

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.<sup>[14,15]</sup> 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<sup>[14]</sup>).

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):

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

where  $C_A$  is the drug concentration in the nano-particle ( $\text{mol}/\text{m}^3$ );  $r$ , the radius of the solid sphere (m); and  $D$  is the diffusion coefficient ( $\text{m}^2/\text{s}$ ) 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  $r=\delta$ ,  $-D_r \frac{\partial C_A}{\partial r} \Big|_{r=\delta} = -D_p \frac{\partial C_A}{\partial r} \Big|_{r=\delta}$
- BC3: at  $r=R$ ,  $-D_p \frac{\partial C_A}{\partial r} \Big|_{r=R} = k_c (C_A^l|_{r=R} - C_A^\infty)$
- 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;  $C_A^l|_{r=R}$  is the drug concentration on the surface of the sphere on the

fluid side;  $C_A^\infty$  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  $C_A^l|_{r=R}$  and  $C_A|_{r=R}$ . One alternative is to assume equilibrium across the interface, that is,

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

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

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

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.<sup>[16]</sup> 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.*,  $C_A^\infty$  is assumed to be negligible [ $C_A^\infty = 0$  in Eq. (3)]. For this laboratory, the students use the 2-D unsteady mass transport by diffusion module in COMSOL<sup>[11]</sup> 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.

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<sup>[11]</sup> 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

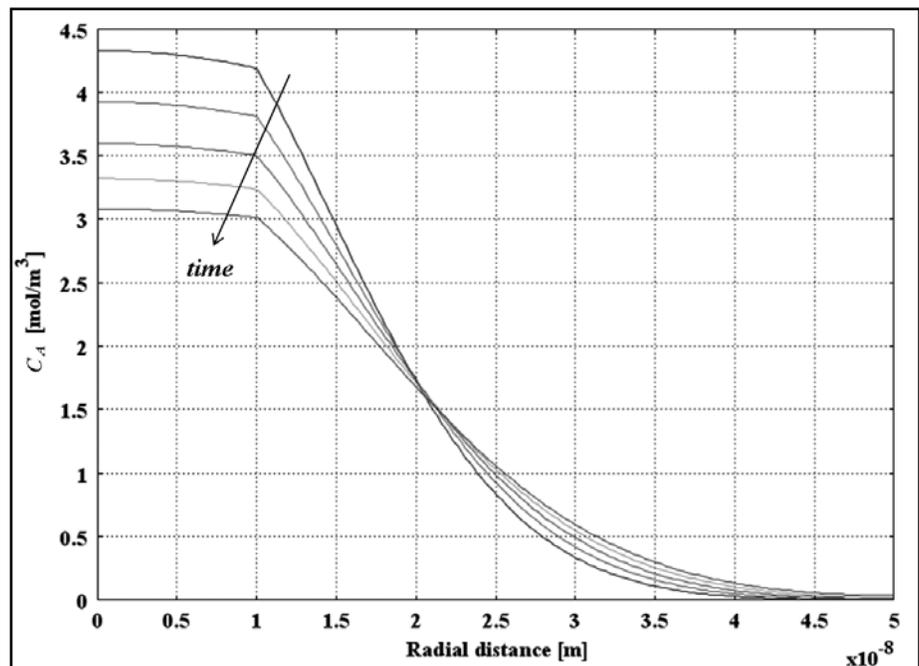


Figure 3. Concentration profile in the nano-particle,  $C_A$ , for different times from 600 – 1000 s.

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.<sup>[11]</sup> 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.

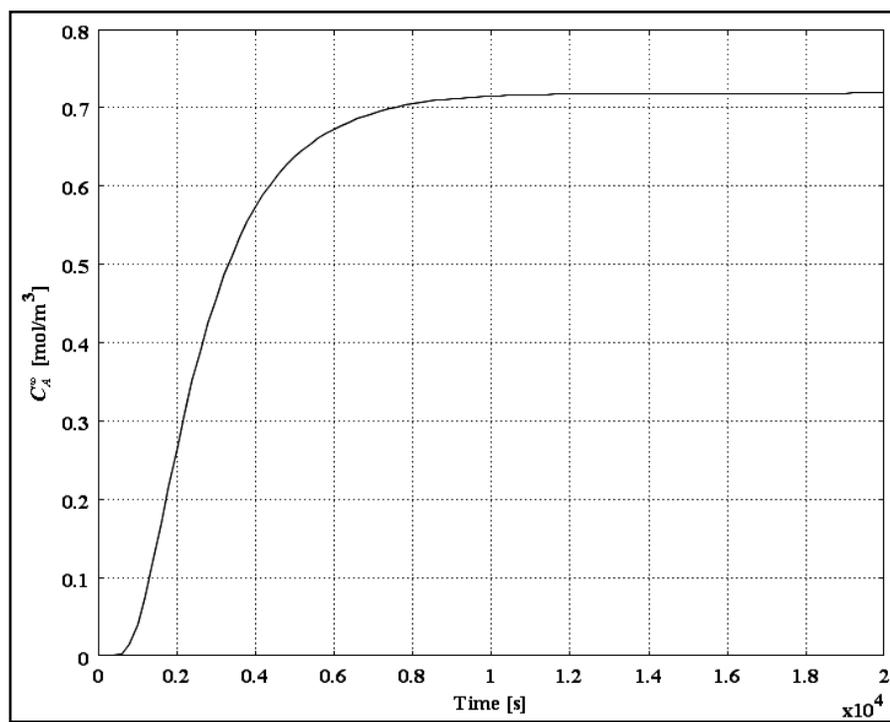


Figure 4. Time-dependent profile of the drug concentration in the tank,  $C_A^\infty$ .

#### 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

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# IDEAS TO CONSIDER FOR NEW CHEMICAL ENGINEERING EDUCATORS: PART 2

## (Courses Offered Later in the Curriculum)

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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<sup>[1]</sup> and published in the 2009 ASEE conference proceedings as paper #AC 2009-29,<sup>[2]</sup> 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<sup>[3]</sup> and is published in the 2008 ASEE Annual Meeting as paper #AC 2008-1147,<sup>[4]</sup> the 2008 AIChE conference proceedings,<sup>[5]</sup> and within the Summer 2009 issue of *Chemical Engineering Education*.<sup>[6]</sup> 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.<sup>[7]</sup>

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

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## 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<sup>[3-6]</sup> 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.<sup>[8]</sup>

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.<sup>[9]</sup>

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

- Show students exceptions to the well-known Le Chatelier's Principle.<sup>[10]</sup>
- Promote a graphical view of thermodynamics that emphasizes uncommon intuition<sup>[11]</sup> and focuses on the benefits of visualization using modern software, such as Mathcad.<sup>[12]</sup>
- Falconer emphasizes the use of concept tests that use classroom response systems to allow immediate feedback from students for formal or informal assessment.<sup>[13]</sup>
- 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.<sup>[14]</sup>
- An MS Excel add-in (XSEOS) calculates a variety of thermodynamic properties using both equations of state and Gibbs excess energy models.<sup>[15]</sup>
- There are various applications of a cubic equation of

state in calculating mixture phase diagrams and chemical equilibrium using MATLAB (with programs provided).<sup>[16]</sup>

- A recent work describes a combination of experimental and modeling approaches to introduce gas-liquid solubility.<sup>[17]</sup>
- Elliott provides an interesting discussion relating solution non-ideality, including hydrogen bonding, to solubility and volatility in both a qualitative and quantitative manner.<sup>[18]</sup>

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<sup>[19]</sup> and a laboratory procedure for gas clathrate hydrates.<sup>[20]</sup> *The Physics Teacher* discusses various fundamental thermodynamics concepts as well as some interesting analyses, such as the thermodynamics of a thermos.<sup>[21]</sup> 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*.<sup>[22]</sup> 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.<sup>[23]</sup>

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.<sup>[24]</sup>

### 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<sup>[15]</sup> or a web applet to determine phase equilibrium from an equation of state may be more appropriate.<sup>[25,26]</sup>
- 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<sup>[27]</sup> 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<sup>[9]</sup> 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*.<sup>[28]</sup> 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,<sup>[29-31]</sup> numerical solutions,<sup>[32, 33]</sup> similarity solutions,<sup>[34]</sup> molecular simulations,<sup>[9, 35, 36]</sup> and desktop modules.<sup>[37]</sup>

- Sinclair<sup>[29]</sup> 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<sup>[30]</sup> utilizes the PDE toolbox feature in Matlab to solve a variety of problems in fluid mechanics, heat transfer, and solid mechanics.
- Keith, et al.,<sup>[31]</sup> 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<sup>[32]</sup> solves free convection problems using similarity variables and a numerical simulation of an initial value problem.
- Binous<sup>[33]</sup> 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<sup>[34]</sup> 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.,<sup>[35]</sup> illustrate the use of molecular-level simulations to predict gas diffusivities.
- Minerick<sup>[37]</sup> 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<sup>[9, 36]</sup> provides relevant Java-based molecular simulations on its website.
- Coker, et al.,<sup>[38, 39]</sup> describe simulation of gas separation using polymer membranes.
- Zheng and Keith<sup>[40-42]</sup> describe the use of Java applets to help students visualize heat and mass transfer.

Two papers by Flynn, et al.,<sup>[43, 44]</sup> focus on integrating green engineering principles into a heat transfer course. The first paper<sup>[43]</sup> describes several traditional heat transfer problems that are uniquely coupled with green engineering principles.<sup>[45, 46]</sup> 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<sup>[44]</sup> 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<sup>[47]</sup>
- Experiments and modeling of lozenge dissolution to simulate drug delivery processes in the human body<sup>[48]</sup>

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

### 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<sup>[55]</sup> or Fogler.<sup>[56]</sup>
- 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.<sup>[40-42, 57]</sup>
- 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.<sup>[31]</sup> 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.<sup>[9, 35, 36]</sup>
- 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<sup>[58-64]</sup> that will now be summarized.

- Stochastic simulations of chemical reactions<sup>[58, 59]</sup>: Martinez-Urreaga, et al.,<sup>[58]</sup> use MATLAB to simulate the reversible reaction  $A \leftrightarrow B$ , while Fan, et al.,<sup>[59]</sup> simulate the thermal death kinetics of a cell population.
- Computational fluid dynamics<sup>[60-62]</sup>: Lawrence, et al.,<sup>[60]</sup> 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.,<sup>[61]</sup> simulate a complex two-dimensional reservoir, determine the residence time distribution and predict the conversion during steady-state operation. Bakker, et al.,<sup>[62]</sup> illustrate non-ideal effects in various reactor types with color images of CFD simulations.
- Parulekar<sup>[63]</sup> 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<sup>[64]</sup> 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<sup>[65]</sup> 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<sup>[66]</sup> 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<sup>[67]</sup> 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.<sup>[68]</sup>

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

- Dartmouth University has an online JAVA periodic table<sup>[69]</sup> that contains puzzles, quizzes, and a molar mass calculator. The same group has a JAVA kinetics plotter<sup>[70]</sup> 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.<sup>[71]</sup> 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.,<sup>[72]</sup> 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.,<sup>[73]</sup> 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.,<sup>[74]</sup> 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.,<sup>[75]</sup> 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.,<sup>[76]</sup> 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<sup>[55]</sup> or Fogler.<sup>[56]</sup>
- 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<sup>[60-62]</sup> 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.<sup>[31]</sup>
- Students are asked to write their own computer programs to simulate temporal evolutions in species concentration and temperature profiles.<sup>[63]</sup>
- An extra emphasis is placed on chemical reactivity and reactor safety.<sup>[62]</sup>
- 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.<sup>[75]</sup>

## 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.<sup>[77]</sup>

- Douglas Cooper (University of Connecticut, *Control Station*,<sup>[78]</sup> and *ControlGuru.com*<sup>[79]</sup>) 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*<sup>[80]</sup>) 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<sup>[77]</sup> 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<sup>[81]</sup>:

- 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.<sup>[82]</sup>

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

Additional laboratory ideas include:

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

Web resources include:

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

Software resources include:

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

### 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.<sup>[94]</sup> 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,<sup>[93]</sup> 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.<sup>[84]</sup> 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,<sup>[96]</sup> Loop-Pro<sup>[93]</sup>) 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.<sup>[97]</sup>*
- *Requiring students to work with technology students at another institution to perform a detailed design of a control system.<sup>[98]</sup>*

### 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 flow-sheet 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,<sup>[99]</sup> process safety,<sup>[100]</sup> Good Manufacturing Practice, Six Sigma,<sup>[101]</sup> optimization,<sup>[102]</sup> selecting materials of construction, reading P&ID’s, heat exchanger network or reactor network synthesis, environmental regulations, engineering ethics, batch scheduling, and product design.<sup>[103]</sup> Senior design is also the last opportunity to reinforce “soft skills” such as teamwork<sup>[104, 105]</sup> and communication.<sup>[106, 107]</sup> Furthermore, the AIChE Centennial Conference has a session on design featuring many of the design textbook authors. Videos of these talks are available online.<sup>[7]</sup>

### 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.<sup>[108]</sup>

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,<sup>[109, 110]</sup> 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.,<sup>[111]</sup> Rogge, et al.,<sup>[112]</sup> and Davis, et al.<sup>[113]</sup>
- 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,<sup>[114]</sup> Rhodes,<sup>[115]</sup> Wibowo and Ng,<sup>[116]</sup> and Hill and Ng.<sup>[117]</sup>

#### Examples of design projects:

- The text by Turton, et al.,<sup>[118]</sup> contains six complete senior design projects in addition to the extensive list of projects on their website.<sup>[119]</sup> Shaeiwitz and Turton<sup>[120]</sup> 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.<sup>[121]</sup>
- The text by Peters, et al.,<sup>[122]</sup> includes problem descriptions for five major projects, five minor design problems, and seven practice-session problems.
- Weiss and Castaldi<sup>[123]</sup> describe a tire gasification senior design project that integrates laboratory experiments and computer simulation.
- Benyahia<sup>[124]</sup> outlines a project involving vinyl chloride monomer (VCM), emphasizing its compliance with ABET 2000 criteria.
- Hernandez, et al.,<sup>[125]</sup> 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,<sup>[126]</sup> the World Congress of Chemical Engineering,<sup>[127]</sup> and NASA<sup>[128]</sup> sponsor annual design competitions. Kundu and Fowler<sup>[129]</sup> discuss the use of engineering design competitions to engage students. Often these involve the use of multidisciplinary teams, which is discussed by Redekopp.<sup>[130]</sup>
- Silverstein<sup>[131]</sup> and Hadley<sup>[132]</sup> describe the use of wikis in senior design as a project-management tool.

Web resources:

- Cadwell, et al.,<sup>[133]</sup> 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,<sup>[134]</sup> the Markkula Center for Applied Ethics,<sup>[135]</sup> and the Center for the Study of Ethics in Society<sup>[136]</sup> 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.<sup>[66]</sup>
- The EPA makes available exposure assessment tools and models.<sup>[137]</sup>
- Miller<sup>[138]</sup> has posted a set of slides on cost estimation.
- Milligan<sup>[139]</sup> hosts a website with specific process equipment costs estimates.
- UT Austin<sup>[140]</sup> 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.<sup>[141]</sup>
- The text and website by Seider, et al.,<sup>[108]</sup> 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,<sup>[142]</sup> and learning styles<sup>[143]</sup> can alleviate potential

problems. An additional suggestion of Sauer and Arce<sup>[144]</sup> 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<sup>[145]</sup> 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*<sup>[146]</sup> (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 work 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 mid-semester 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<sup>[147, 148]</sup> 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.<sup>[149, 150]</sup> In addition, students are provided with exemplary documents from a previous year that demonstrate expectations.**
- **The text by Turton, et al.,<sup>[118]</sup> 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<sup>[151]</sup> is a useful database for equipment vendors.**
- **Bullard, et al.,<sup>[152]</sup> 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.

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**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

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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.<sup>[1]</sup> 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.<sup>[2]</sup>

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.<sup>[3]</sup> For advanced devices, alkaline  $\text{MnO}_2$ –Zn batteries are preferred, which use electrolytic manganese dioxide (EMD) and an alkaline electrolyte (KOH).<sup>[4]</sup> When used with the electric grid, batteries are able to enhance technologies related to wind

power, solar power, and peak load shifting.<sup>[5]</sup> These topics provide students with exceptional platforms to which they can relate their investigations to contemporary issues.

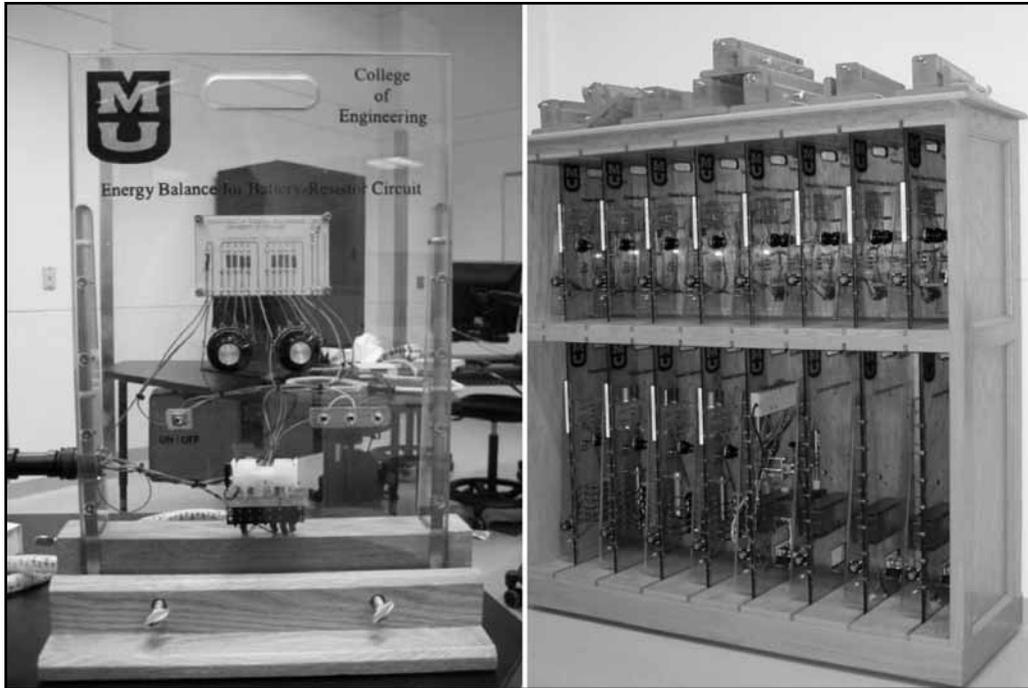
The battery-resistor circuit module allows heat transfer, mass transfer, reactions, circuit theory, heat/mass balances, and product design to be studied in a single module. The module also provides a good preparation for the study of sensors, biosensors, and instrumentation because of its integrated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

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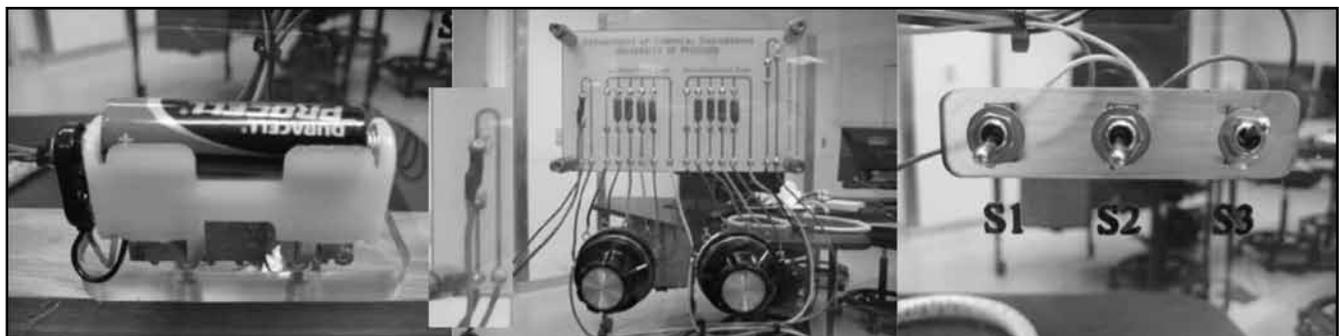
**Michelle Ji** is an M.S. candidate in chemical engineering at MU with anticipated graduation in 2011. She received her B.S. in biological engineering at MU in 2009.

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**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.<sup>[6]</sup>

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:

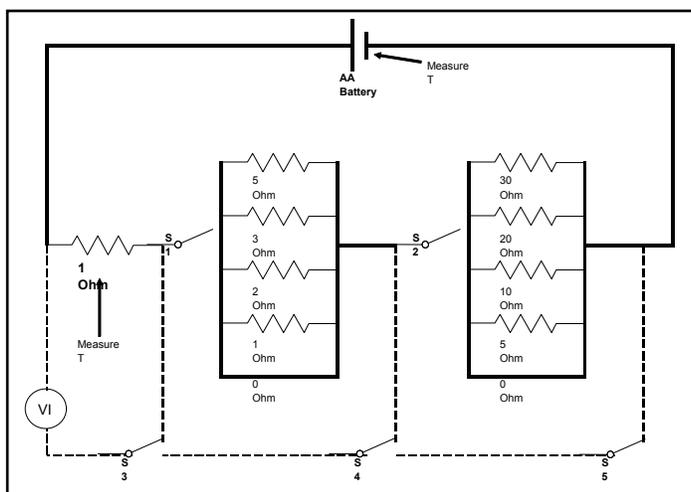
1. Insert and fasten the module on a base at a workstation and connect the 24-pin connector that links the module to the National Instruments based data acquisition system.
2. Place AA battery in the battery holder or connect ancillary battery to system.
3. Start module-specific LabVIEW virtual instrument 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.<sup>[7]</sup>

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;  $\frac{dU}{dt}$ .<sup>[8]</sup> 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.

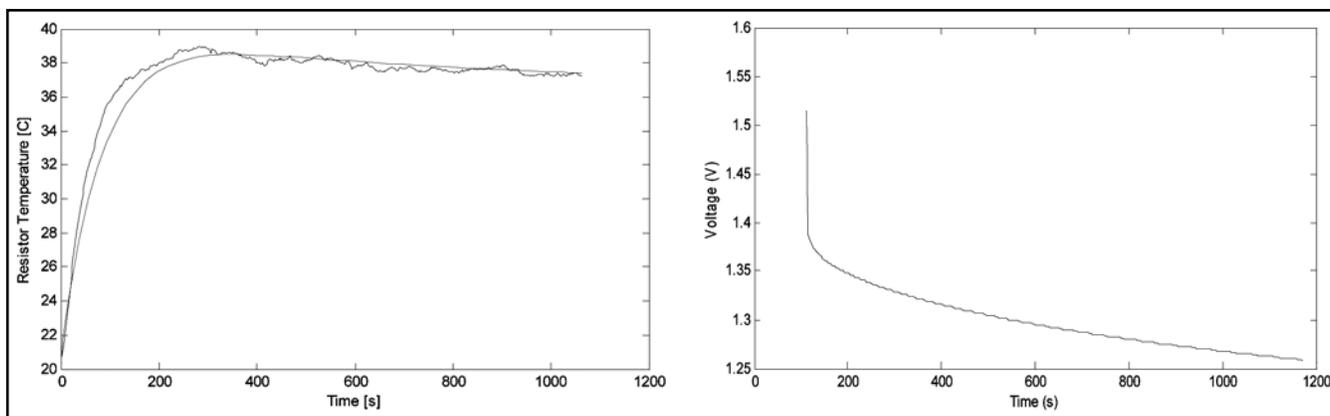
The following are pertinent governing equations:

$$\frac{dU}{dt} = Q - W \quad (1)$$

$$\frac{m_{res} C_{res} dT_{res}}{dt} = Q - W \quad (2)$$

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

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.<sup>[9]</sup> 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.<sup>[2]</sup>



**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.

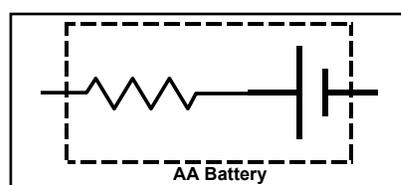
Figure 4 provides a typical resistor temperature vs. time profile and a voltage profile for battery discharge operating with a 3-ohm total resistance load.

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.<sup>[10]</sup> 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.<sup>[11]</sup>

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.<sup>[12]</sup>

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.<sup>[13]</sup>

## 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.<sup>[14]</sup> Where:

$$V_o = I(R_{\text{Battery}} + R_{\text{Circuit}}) \quad (4)$$

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:

$$I = V_{\text{Circuit}} / R_{\text{Circuit}} \quad (5)$$

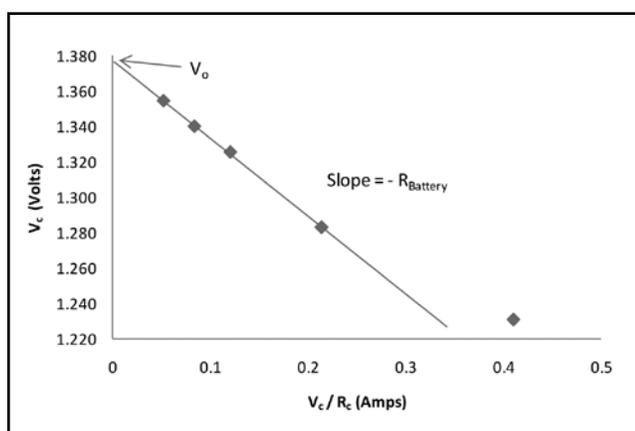
or

$$V_{\text{Circuit}} = V_o - R_{\text{Battery}} (V_{\text{Circuit}} / R_{\text{Circuit}}) \quad (6)$$

where linear regression can be used to identify  $V_o$  (constant) and  $R_{\text{Battery}}$  (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.<sup>[15]</sup> 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.<sup>[16]</sup> Detailed discussions related to transient diffusions in packed-bed anodes could be used to explain the dependence of



**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.

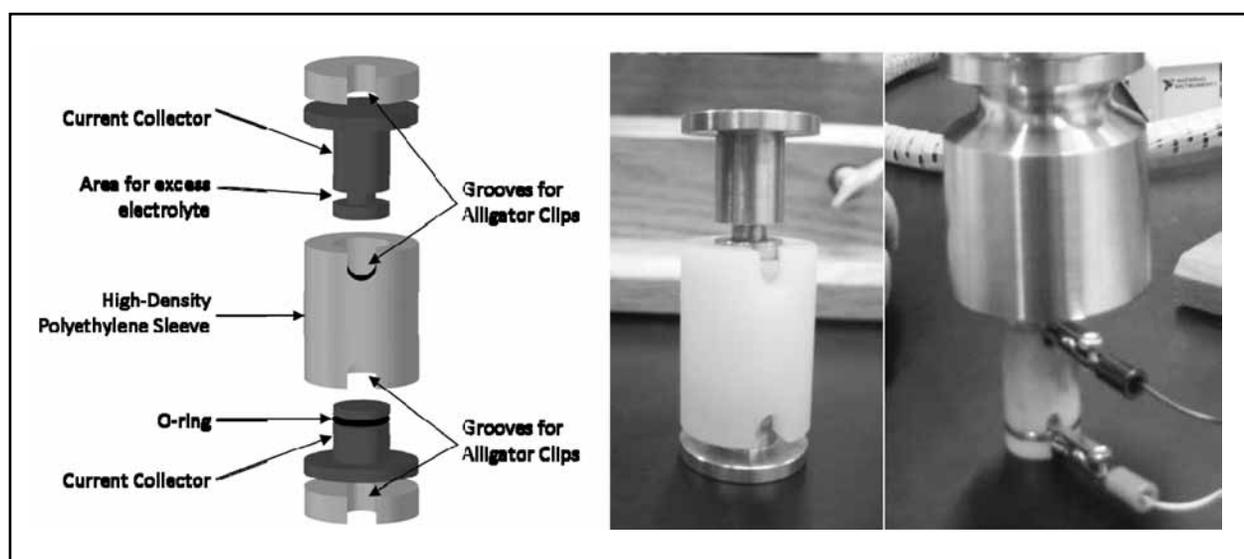
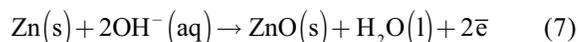
the internal battery resistance on time. If the students are able to do the sophisticated modeling, the diffusion in the packed bed could be modeled, converted to diffusion over-potential, and interpreted in terms of a resistor model.

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

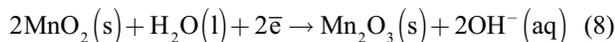
The objective of this project is to evaluate batteries that the students assemble. The students are also to relate fundamental differences of the battery performances to properties of the materials and the cell geometry, and to quantitatively correlate the performance to diffusivity resulting from varying 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.<sup>[17]</sup>

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<sub>2</sub> 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.<sup>[18]</sup> 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:<sup>[19]</sup>



**Figure 7.** Pictorial representation of a compression cell used for the assembly of MnO<sub>2</sub> – Zn batteries (left) with picture of assembled cell (middle) and an assembled cell with weight to provide compression (right).

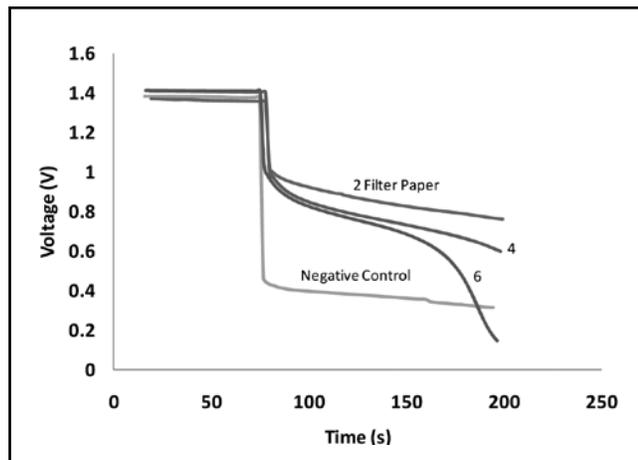


Manganese oxide powder mixed with a carbon black is used as the cathode. The carbon is used to increase conductivity of the positive active mass to reduce the internal resistance of the cell.<sup>[20]</sup> This material may require mechanical processing to maximize reactivity.<sup>[21]</sup> Potassium hydroxide (1M or 2M) in distilled water works well as the electrolyte because of its high conductivity, and results in a low internal resistance.<sup>[22]</sup> In the presence of KOH, the discharge behavior of  $\text{MnO}_2$  occurs in a heterogeneous phase reaction.<sup>[23]</sup>

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.<sup>[15]</sup> 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 ( $\text{MnO}_2$ ) into the cylinder (enough to cover a



**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.

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.<sup>[24]</sup>

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.<sup>[15]</sup> 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.<sup>[15]</sup> 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 encoun-

tered 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.

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## 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. □

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*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.*

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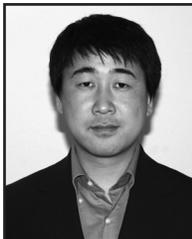
*Teaching and research assistantships as well as industrially sponsored fellowships available. In addition to stipends, tuition and fees are waived. PhD students may get some incentive scholarships.*

**Chairman, Graduate Committee**  
**Department of Chemical and Biomolecular Engineering**  
**The University of Akron**  
**Akron, OH 44325-3906**  
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 Nanomedicine



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 Processing,  
 Polymerization in Nanostruc-  
 tured Fluids, Supercritical  
 Fluid Processing



## Graduate Education in Chemical and Biomolecular Engineering

**S. S. C. CHUANG**  
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 gineering, Environmen-  
 tally Benign Synthesis,  
 Fuel Cell



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 Molecular Simulation,  
 Phase Behavior, Physi-  
 cal Properties, Process  
 Modeling, Supercritical  
 Fluids



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



**L.-K. JU**  
 Renewable Bioenergy,  
 Environmental  
 Bioengineering  
  
 Department Chair



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



**L. LIU**  
 Biointerfaces,  
 Biomaterials, Biosen-  
 sors, Tissue Engineering



**C. MONTY**  
 Reaction Engineering, Bio-  
 mimicry, Microsensors



**B. Z. NEWBY**  
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 tive Patterning, AntiFouling  
 Coatings, Gradient Surfaces



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 Systems Health Monitoring  
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 Materials Performance  
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 Nonlinear Control,  
 Chaotic Processes,  
 Engineering Education



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



**J. ZHENG**  
 Computational Biophysics,  
 Biomolecular Interfaces,  
 Biomaterials



# THE UNIVERSITY OF ALABAMA

## Chemical & Biological Engineering

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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<sub>2</sub> 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



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hturner@eng.ua.edu  
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# 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**.

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have a broad range of  
research interests.  
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biotechnology** related areas.

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provides a strong potential  
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graduate students to apply  
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near the **NASA Marshall**

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also in proximity to over **200 high-technology  
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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  
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<http://www.uah.edu>  
<http://www.che.uah.edu>





## UNIVERSITY OF ALBERTA



Our Department of Chemical and Materials Engineering offers students the opportunity to **study** and conduct **leading research** with **world-class academics** in the **top program** in Canada, and one of the very best in North America. Our graduate student population is culturally diverse, academically strong, innovative, creative, and is drawn to our challenging and supportive environment from all areas of the world.

► Degrees are offered at the MSc and PhD levels in **chemical engineering, materials engineering, and process control**.

► All full-time graduate students in **research programs** receive a **stipend** to cover living expenses and tuition.

Our graduates are sought-after professionals who will be international leaders of tomorrow's chemical and materials engineering advances. Research topics include:

biomaterials, biotechnology, coal combustion, colloids and interfacial phenomenon, computational chemistry, computational fluid dynamics, computer process control, corrosion and wear engineering, drug delivery, electrochemistry, fluid-particle dynamics, fuel cell modeling and control, heavy oil processing and upgrading, heterogeneous catalysis, hydrogen storage materials, materials processing, micro-alloy steels, micromechanics, mineral processing, molecular sieves, multiphase mixing, nanostructured biomaterials, oil sands, petroleum thermodynamics, pollution control, polymers, powder metallurgy, process and performance monitoring, rheology, surface science, system identification, thermodynamics, and transport phenomena.

► The Faculty of Engineering has added more than **one million square feet** of **outstanding teaching, research, and personnel space** in the past six years. We offer **outstanding** and **unique experimental and computational facilities**, including access to one of the most technologically advanced nanotechnology facilities in the world – the **National Institute for Nanotechnology**, connected by pedway to the Chemical and Materials Engineering Building.

► Annual research funding for our Department is over **\$14 million**. Externally sponsored funding to support engineering research in the entire Faculty of Engineering has increased to **over \$50 million** each year—the **largest amount** of any Faculty of Engineering in Canada.

### For further information, contact:

Graduate Program Office  
Department of Chemical and Materials Engineering  
University of Alberta  
Edmonton, Alberta, Canada T6G 2G6  
Phone: 780-492-1823 Fax: 780-492-2881  
[www.cme.engineering.ualberta.ca](http://www.cme.engineering.ualberta.ca)

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R.E. Burrell, PhD (University of Waterloo)  
K. Cadien, PhD (University of Illinois at Champaign-Urbana)  
W. Chen, PhD (University of Manitoba)  
P. Choi, PhD (University of Waterloo)  
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J. Ryan, PhD (University of Missouri) *Emeritus*  
S. Sanders, PhD (University of Alberta)  
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J.M. Shaw, PhD (University of British Columbia)  
H. Uludag, PhD (University of Toronto)  
L. Unsworth, PhD (McMaster University)  
S.E. Wanke, PhD (University of California, Davis) *Emeritus*  
M. Wayman, PhD (University of Cambridge) *Emeritus*  
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R. Wood, PhD (Northwestern University) *Emeritus*  
Z. Xu, PhD (Virginia Polytechnic Institute and State University)  
T. Yeung, PhD (University of British Columbia)  
H. Zeng, PhD (University of California, Santa Barbara)  
H. Zhang, PhD (Princeton University)

## 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 PHILIPPOSIAN**, 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**  
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## *Chemical and Environmental Engineering at*

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**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.*



## 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.

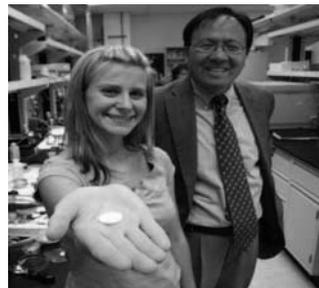
Protein engineering, biomedical engineering, enzyme kinetics, antibody engineering

**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



Graduate Program in the Ralph E. Martin Department of Chemical Engineering

# University of Arkansas



The Department of Chemical Engineering at the University of Arkansas offers graduate programs leading to M.S. and Ph.D. Degrees.

Qualified applicants are eligible for financial aid. Annual departmental Ph.D. stipends provide \$20,000, Doctoral Academy Fellowships provide up to \$30,000, and Distinguished Doctoral Fellowships provide \$40,000. For stipend and fellowship recipients, all tuition is waived. Applications received before April 1 will be given first consideration.

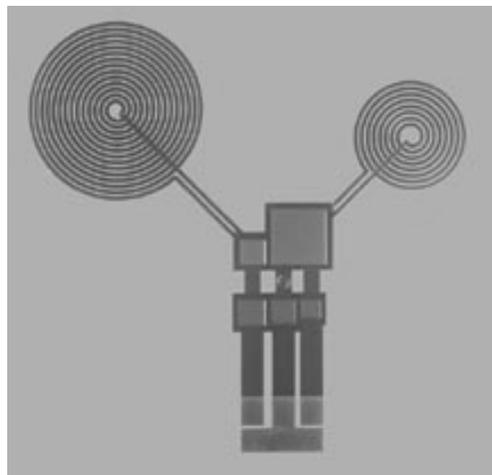
## Areas of Research

- Biochemical engineering
- Biological and food systems
- Biomaterials
- Biomolecular nanophonics
- Electronic materials processing
- Fate of pollutants in the environment
- Hazardous chemical release consequence analysis
- Integrated passive electronic components
- Membrane separations
- Micro channel electrophoresis
- Supercritical fluid technology
- Phase equilibria and process design



## Faculty

M.D. Ackerson  
R.E. Babcock  
R.R. Beitle  
E.C. Clausen  
J.A. Havens  
C.N. Hestekin  
J.A. Hestekin  
J.W. King  
W.R. Penney  
D.K. Roper  
S.L. Servoss  
T.O. Spicer  
G.J. Thoma  
R.K. Ulrich



### For more information contact

Dr. Richard Ulrich <rulrich@uark.edu> or 479-575-5645  
Chemical Engineering Graduate Program Information: <http://www.cheg.uark.edu/graduate.asp>

# AUBURN UNIVERSITY Chemical Engineering



## Faculty

W. Robert Ashurst — *University of California, Berkeley*  
Mark E. Byrne — *Purdue University*  
Robert P. Chambers — *University of California, Berkeley*  
Harry T. Cullinan — *Carnegie Institute of Technology*  
Virginia Davis — *Rice University*  
Steve R. Duke — *University of Illinois at Urbana-Champaign*  
Mario R. Eden — *Technical University of Denmark*  
Ram B. Gupta — *University of Texas at Austin*  
Thomas R. Hanley — *Virginia Tech Institute*  
Yoon Y. Lee — *Iowa State University*  
Elizabeth A. Lipke — *Rice University*  
Glennon Maples — *Oklahoma State University*  
Ronald D. Neuman — *The Institute of Paper Chemistry*  
Timothy D. Placek — *University of Kentucky*  
Christopher B. Roberts — *University of Notre Dame*  
Bruce J. Tatarchuk — *University of Wisconsin*  
Jin Wang — *University of Texas at Austin*

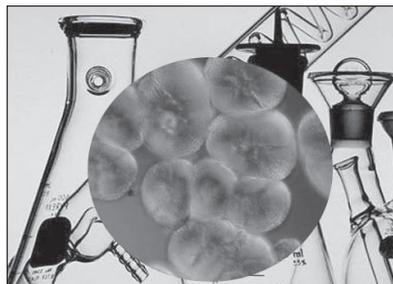


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## Research Areas

- Alternative Energy and Fuels
- Biochemical Engineering
- Biomaterials
- Biomedical Engineering
- Bioprocessing and Bioenergy
- Catalysis and Reaction Engineering
- Computer-Aided Engineering
- Drug Delivery
- Energy Conversion and Storage
- Environmental Biotechnology
- Fuel Cells
- Green Chemistry
- Materials
- MEMS and NEMS
- Microfibrous Materials
- Nanotechnology
- Polymers
- Process Control
- Pulp and Paper
- Supercritical Fluids
- Surface and Interfacial Science
- Sustainable Engineering
- Molecular Thermodynamics

### For more information:

Director of Graduate Recruiting  
Department of Chemical Engineering  
Auburn, AL 36849-5127  
Phone 334.844.4827  
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[www.eng.auburn.edu/chen](http://www.eng.auburn.edu/chen)  
[chemical@eng.auburn.edu](mailto:chemical@eng.auburn.edu)

Financial assistance is available to qualified applicants.



**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 Paralympic 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)  
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 Richard Kerekes (McGill)  
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 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

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**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*

## FACULTY

**U. Sundararaj**, Head (*Minnesota*)  
**J. Abedi** (*Toronto*)  
**R. Aguilera** (*Colorado School*)  
**J. Azaiez** (*Stanford*)  
**L. A. Behie** (*Western Ontario*)  
**C. Bellehumeur** (*McMaster*)  
**J. Bergerson** (*Carnegie-Mellon*)  
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**M. Clarke** (*Calgary*)  
**A. De Visscher** (*Ghent, Belgium*)  
**M. Dong** (*Waterloo*)  
**M. W. Foley** (*Queens*)  
**I. D. Gates** (*Minnesota*)  
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**M. Husein** (*McGill*)  
**L. James** (*Waterloo*)  
**A. A. Jeje** (*MIT*)  
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**M. S. Kallos** (*Calgary*)  
**A. Kantzas** (*Waterloo*)  
**D. Keith** (*MIT*)  
**R. Krenz** (*Calgary*)  
**N. Mahinpey** (*Toronto*)  
**B. B. Maini** (*Univ. Washington*)  
**A. K. Mehrotra** (*Calgary*)  
**S. A. Mehta** (*Calgary*)  
**R. G. Moore** (*Alberta*)  
**P. Pereira** (*France*)  
**M. Pooladi-Darvish** (*Alberta*)  
**K. D. Rinker** (*North Carolina*)  
**M. Satyro** (*Calgary*)  
**A. Sen** (*Calgary*)  
**A. Settari** (*Calgary*)  
**H. W. Yarranton** (*Alberta*)  
**L. Zanzotto** (*Czechoslovakia*)

## DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

The Department offers graduate programs leading to the M.Sc., M.Eng., and Ph.D. degrees with Specializations in Chemical Engineering, Petroleum Engineering, Energy & Environmental Engineering, and Biomedical Engineering. Financial assistance is available to all qualified applicants. The areas of research include:

- catalysis; modeling, simulation & optimization; process control & dynamics; reaction engineering & chemical kinetics; rheology (polymers, suspensions & emulsions); separation operations; thermodynamics & phase equilibria; transport phenomena (deposition in pipelines, diffusion, dispersion, flow in porous media, heat transfer), nanotechnology, nanoparticle research, polymer nanocomposites;
- drilling engineering; improved gas recovery (coal bed methane, gas hydrates, tight gas); improved oil recovery (SAGD, VAPEX, EOR, in-situ combustion); production engineering; reservoir characterization; reservoir engineering & modeling; reservoir geomechanics & simulation;
- air pollution control; alternate energy sources; greenhouse gas control & CO<sub>2</sub> sequestration; life cycle assessment; petroleum waste management & site remediation; solid waste management; water & wastewater treatment
- cell & tissue engineering (cardiovascular systems, bone & joint repair); bacterial infection; biopolymers; bioproduct development; blood filtration; microvascular systems; stem cell bioprocess engineering (media & reagent development, bioreactor protocols) .

### *For Additional Information, Contact:*

Dr. J. Azaiez, Associate Head, Graduate Studies  
Department of Chemical and Petroleum Engineering  
University of Calgary, Calgary, AB, Canada T2N 1N4  
gradstud@ucalgary.ca ; www.schulich.ucalgary.ca/ench/

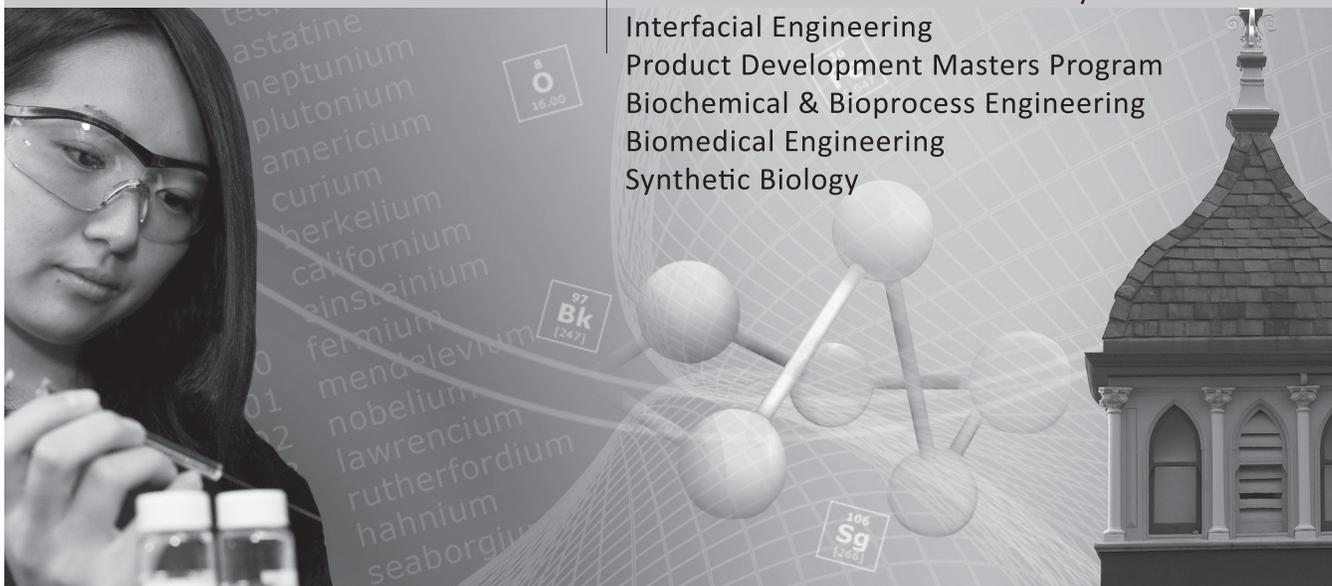


**SCHULICH**  
School of Engineering



*The University is located in Calgary, which is the Oil and Engineering Capital of Canada, and the home of the world famous Calgary Stampede and the 1988 Winter Olympics. With a population of over one million, the City combines the traditions of the Old West with the sophistication of a modern urban center. Beautiful Banff National Park is 110 km west of the City. The ski resorts and numerous hiking trails in Banff, Lake Louise, and Kananaskis areas are readily accessible. In the above photo of the University Campus, the Engineering Complex is located in the top left.*

Catalysis and Reaction Engineering  
Electrochemical Engineering  
Polymers and Complex Fluids  
Microsystems Technology and Microelectronics  
Molecular Simulations and Theory  
Interfacial Engineering  
Product Development Masters Program  
Biochemical & Bioprocess Engineering  
Biomedical Engineering  
Synthetic Biology



study **Chemical & Biomolecular  
Engineering**

at the **University of California, Berkeley**



The Chemical & Biomolecular Engineering Department at the University of California, Berkeley, one of the preeminent departments in the field, offers graduate programs leading to the Doctor of Philosophy or a Master of Science in Product Development.

For more information visit our website at:

<http://cheme.berkeley.edu>

# 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

## 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.



## 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**

## 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](http://www.chemeng.ucla.edu)

# LIVING THE PROMISE

Clean Air, Fresh Water, Good Health and Sustainable Energy



## CHEMICAL AND ENVIRONMENTAL ENGINEERING

### RESEARCH FOR A GREENER WORLD

The Department of Chemical and Environmental Engineering at the University of California Riverside is at the forefront of our nation's commitment to energy independence and sustainability.

Our four fields of application — clean air, fresh water, human health and sustainable energy — are supported by six core areas of research strength:

Air Quality Systems, Advanced Materials and Nanotechnology, Biotechnology, Energy Systems, Theory and Molecular Modeling, and Water Quality Systems.

### WE ENGINEER EXCELLENCE

The Graduate Program offers the M.S. and Ph.D. degrees in Chemical and Environmental Engineering. Graduates of the program in Chemical and Environmental Engineering are ready for careers in the fastest growing sectors of engineering with salaries among the highest of all college graduates. And they are fully prepared to contribute to the nation's priority challenges in energy, security, clean air and water...or anything else.

### UC RIVERSIDE



The University of California, Riverside (UCR) is the fastest growing and most ethnically diverse of the 10 campuses of the University of California. UCR is located on over 1,100 acres at the foot of the Box Springs Mountains, about 50 miles east of Los Angeles. Our picturesque campus is virtually equidistant from the desert, the mountains, and the ocean. UCR provides an ideal setting for students, faculty, and staff seeking to study, work, and live in a community steeped in rich heritage that offers a dynamic mix of arts and entertainment and an opportunity for affordable living.

### INNOVATIVE FACULTY

Our faculty are leaders in innovative methods of air and water pollution control, making breakthroughs in commercializable fuel cell technologies, applying nanoscientific principles to create new sensors of toxic substances, and advancing the development of economical and clean renewable fuels and energy.

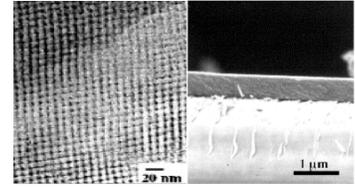
- Akua Asa-Awuku (Georgia Tech): *Aerosol-cloud climate interactions and particulate hygroscopicity; droplet growth kinetics*
- Wilfred Chen (Caltech): *Environmental biotechnology; microbial engineering*
- David Cocker (Caltech): *Air quality systems engineering; atmospheric chemistry*
- David Cwiertny (Johns Hopkins): *Environmental chemistry; pollutant fate and transport; ground water remediation*
- Robert Haddon (Penn State): *Carbon nanotubes; applied materials*
- David Kisailus (UC Santa Barbara): *Bio-mimetics; bio-inspired materials synthesis for nanomaterials; energy storage/conversion*
- Mark Matsumoto (UC Davis): *Water and wastewater treatment; soil remediation; hazardous waste*
- Ashok Mulchandani (McGill): *Bioengineering; biomaterials; biosensors; environmental biotechnology*
- Nosang Myung (UCLA): *Material electrochemistry; MEMS/NEMS; sensors; nanowires; thermoelectric materials*
- Joseph Norbeck (Nebraska): *Advanced vehicle technology; air pollution; renewable fuels*
- Sharon Walker (Yale): *Bacterial transport in natural and engineered systems; water quality engineering*
- Jianzhong Wu (UC Berkeley): *Molecular modeling; nanomaterials; theory of complex fluids*
- Charles Wyman (Princeton): *Sustainable production of fuels and chemicals; pretreatment and conversion of celluloses*
- Yushan Yan (Caltech): *Zeolite thin films; fuel cells; nanostructured materials*

**WEB** [WWW.CEE.UCR.EDU](http://WWW.CEE.UCR.EDU)

**E-MAIL** [GRADCEE@ENGR.UCR.EDU](mailto:GRADCEE@ENGR.UCR.EDU)

**APPLY** [HTTPS://GRADSYS.UCR.EDU](https://GRADSYS.UCR.EDU)

# UC SANTA BARBARA chemical engineering



SBA-16 (cubic mesoporous silica)

## Award-winning faculty

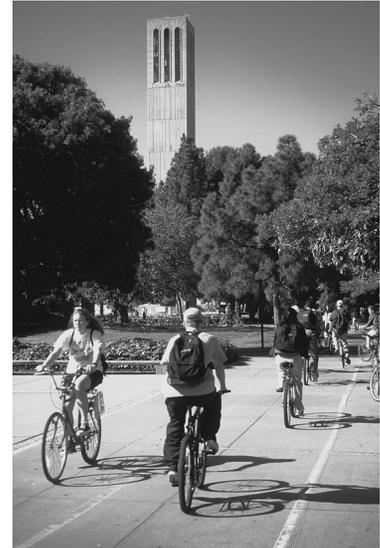
Bradley F. Chmelka  
Patrick S. Daugherty  
Michael F. Doherty  
Francis J. Doyle III  
Glenn H. Fredrickson, NAE  
Michael J. Gordon  
Song-I Han  
Jacob Israelachvili, NAE, NAS, FRS  
Edward J. Kramer, NAE  
L. Gary Leal, NAE  
Glenn E. Lucas  
Eric McFarland  
Samir Mitragotri  
Baron G. Peters  
Susannah L. Scott  
M. Scott Shell  
Todd M. Squires  
Theofanis G. Theofanous, NAE  
Joseph A. Zasadzinski

## Research strengths

Biomaterials  
Bioengineering  
Catalysis  
Renewable energy  
Complex fluids  
Polymers  
Electronic and optical materials  
Fluids and transport  
Process systems engineering  
Surfaces and thin films

## Interdisciplinary research

California Nanosystems Institute  
Center for Control Engineering  
and Computation  
Center for Polymers and Organic Solids  
Center for Risk Studies and Safety  
Institute for Collaborative Biotechnologies  
Institute for Energy Efficiency  
Institute for Quantum Engineering,  
Science & Technology  
International Center for Materials Research  
Kavli Institute for Theoretical Physics  
Materials Research Laboratory



*Interdisciplinary research and entrepreneurship are hallmarks of Engineering at UC Santa Barbara. Many graduate students choose to be co-advised.*



*The UCSB campus, located on the Pacific Coast about 100 miles northwest of Los Angeles, has more than 20,000 students.*

Doctoral students in good academic standing receive financial support via teaching and research assistantships. For additional information and to complete an application, visit [www.chemengr.ucsb.edu](http://www.chemengr.ucsb.edu) or contact [chegrads@engineering.ucsb.edu](mailto:chegrads@engineering.ucsb.edu)



# CALTECH CHEMICAL ENGINEERING

*“At the Leading Edge”*

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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

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Department of Chemical Engineering  
Pittsburgh, PA 15213-3890

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- > 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](http://www.cheme.cmu.edu)
- Online Graduate Application**  
[www.cheme.edu/admissions](http://www.cheme.edu/admissions)

- Contact Information**  
[chegrad@andrew.cmu.edu](mailto:chegrad@andrew.cmu.edu)  
412.268.2230

**START GAME**

# Case Western Reserve University

Advanced Research in Energy, Materials, and Bio-related applications



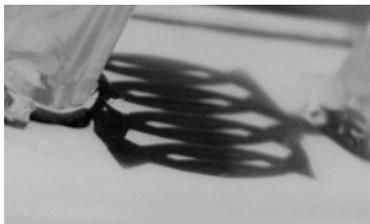
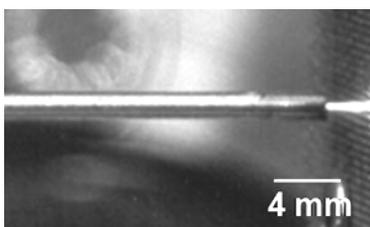
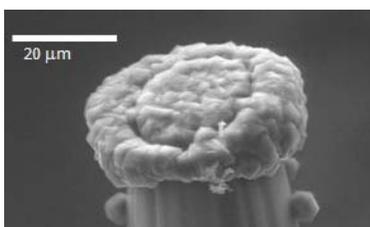
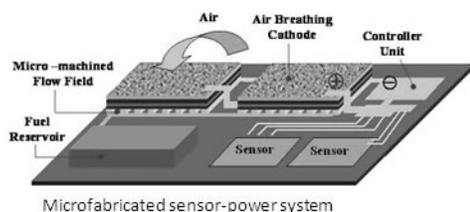
The graduate programs in Chemical Engineering at Case Western Reserve University prepare students for an independent, creative career in chemical engineering research in industry or academia. Research opportunities, especially in our core strengths of energy, advanced materials, and biological applications 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-Chiu 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>



## 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



# 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.*



**FACULTY**

Sanjoy Banerjee

Alexander Couzis

Morton M. Denn

M. Lane Gilchrist

Ilona Kretzschmar

Jae W. Lee

Charles Maldarelli

Jeffrey F. Morris

Irven H. Rinard

David S. Rumschitzki

Carol A. Steiner

Daniel A. Steingart

Gabriel I. Tardos

Raymond S. Tu

**RESEARCH AREAS**

**Biomaterials and Biotransport**

atherogenesis, bio-fluid flow, self-assembled biomaterials

**Colloid Science and Engineering**

directed assembly, novel particle technology

**Complex Fluids and Multiphase Flow**

boiling heat transfer, emulsions, rheology, suspensions

**Energy Generation and Storage**

batteries, gas hydrates, thermal energy storage

**Interfacial Phenomena and Soft Matter**

device design, dynamic interfacial processes

**Nanomaterials and Self Assembly**

catalysts, patchy particles, sensors

**Polymer Science and Engineering**

polymer processing, rheology

**Powder Science and Technology**

pharmaceutical formulations, powder flow

**Process Design and Optimization**

environmental plant design, process intensification

**INSTITUTES**

**Levich Institute for Physicochemical Hydrodynamics**

directed by Morton M. Denn  
Albert Einstein Professor of Science and Engineering

**Energy Institute**

directed by Sanjoy Banerjee  
Distinguished Professor of Chemical Engineering



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[gradinfo@che.ccnycuny.edu](mailto:gradinfo@che.ccnycuny.edu)

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# CLEMSON<sup>®</sup>

## CHEMICAL AND BIOMOLECULAR ENGINEERING

Clemson University boasts a 1,400 acre campus on the shores of Lake Hartwell at the foothills of the Blue Ridge Mountains. The warm campus environment, great weather, and recreational activities make Clemson University an ideal place to live and learn.

### ChBE GRADUATE PROGRAM

The Department of Chemical and Biomolecular Engineering offers strong research programs in biotechnology, advanced materials, energy and chemical processing.

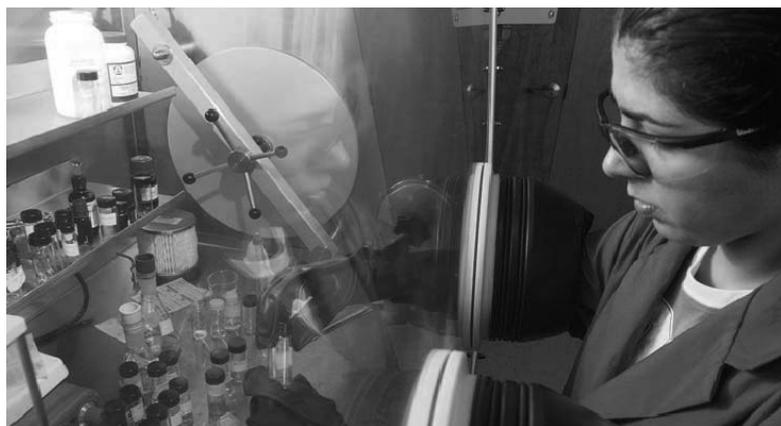
**Biotechnology:** bioelectronics, biosensors and biochips, biopolymers, drug delivery, bone and tissue regeneration, bioseparations

**Advanced materials:** polymer fibers, films and composites, nanoscale design of catalysts, biomaterials, nanomaterials, membranes, directed assembly, interfacial engineering, molecular modeling and simulation

**Energy:** hydrogen production and storage, biofuels synthesis, sustainable engineering, quantum and molecular modeling, nanotechnology and reaction engineering

**Chemical processing:** separations, kinetics and catalysis, process design and analysis and product design.

Learn more at  
[www.clemson.edu/ces/departments/chbe](http://www.clemson.edu/ces/departments/chbe)



### Clemson ChBE Faculty

David A. Bruce, *Professor*  
Charles H. Gooding, *Professor*  
James G. Goodwin, *Professor*  
Anthony Guiseppi-Elie, *Prof. & C3B Dir.*  
Esin Gulari, *Professor & Dean*  
Graham M. Harrison, *Assoc. Professor*  
Douglas E. Hirt, *Professor & Chair*  
Scott M. Husson, *Prof. & Grad. Coord.*  
Christopher L. Kitchens, *Assist. Professor*  
Amod A. Ogale, *Professor & CAEFF Dir.*  
Mark E. Roberts, *Assist. Professor*  
Mark C. Thies, *Professor*

### For More Information, Contact:

Graduate Coordinator  
shusson@clemson.edu  
864-656-3055

Department of Chemical and Biomolecular  
Engineering  
Clemson University, Box 340909  
Clemson, South Carolina 29634

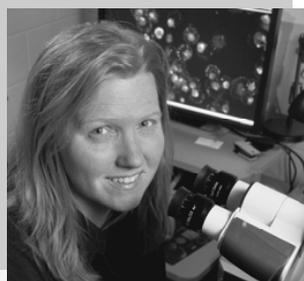
# University of Colorado at Boulder

## Why the University of Colorado?

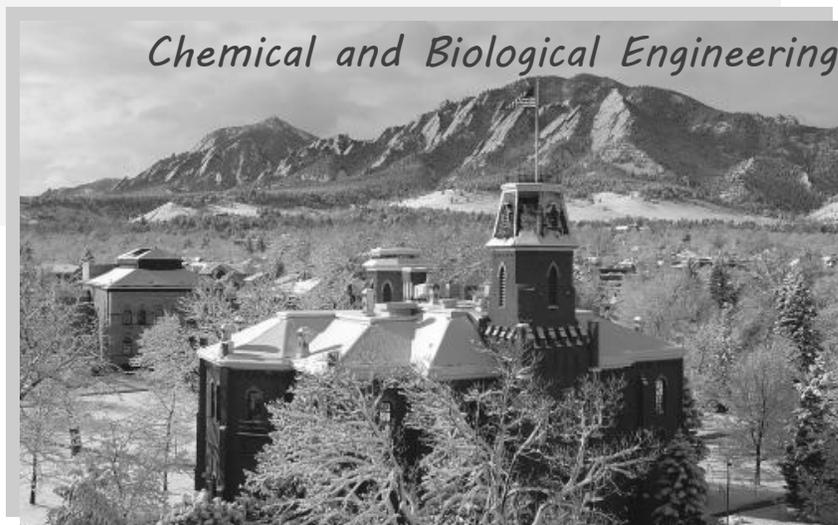
- Diverse research thrusts and expertise
- Nationally recognized faculty in research and teaching
- Collegiality between faculty, staff, and students

## 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*

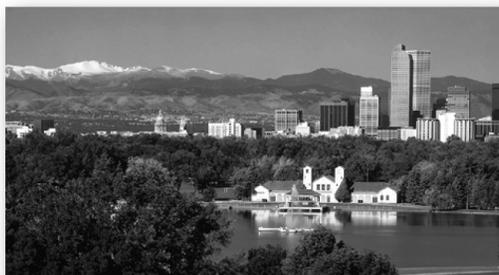


Professor Kristi Anseth, member of the National Academy of Engineering and National Institute of Medicine



Engineering Center, ECCH 111 · University of Colorado at Boulder · Boulder, CO 80309-0424

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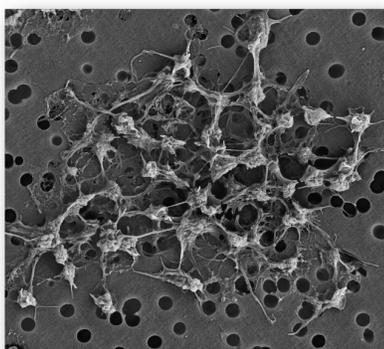
Evolving from its origins as a school of mining founded in 1873, CSM is a unique, highly-focused University dedicated to scholarship and research in materials, energy, and the environment.



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

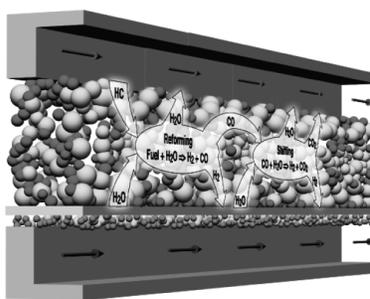
Microfluidics (Marr, Neeves)  
 Biological membranes (Sum)

## 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)



# 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

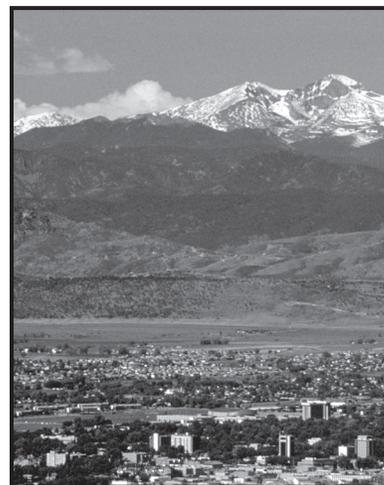
Research Assistantships pay a competitive stipend. Students on assistantships also receive tuition support. The department has a number of research assistantships. Students select research projects in their area of interest from which a thesis or dissertation may be developed. Additional University fellowship 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](mailto:cbe_grad@colostate.edu)



# COLUMBIA UNIVERSITY

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Graduate Programs in Chemical Engineering  
M.S. and PhD Programs



## Faculty and Research Areas

- S. BANTA • Protein & Metabolic Engineering
- C.J. DURNING • Polymer Physical Chemistry
- G. FLYNN • Physical Chemistry
- J. JU • Genomics
- J. KOBERSTEIN • Polymers, Biomaterials, Surfaces, Membranes
- S.K. KUMAR • Synthetic & Natural Polymers, Nanomaterials
- E.F. LEONARD • Biomedical Engineering, Transport Phenomena
- V. FAYE MCNEILL • Environmental Chemical Engineering, Atmospheric Chemistry, Aerosols
- V. ORTIZ • Molecular Modeling, Thermodynamics & Statistical Mechanics in Biology
- B. O'SHAUGHNESSY • Polymer Physics
- A.-H. ALISSA PARK • Sustainable Energy, Carbon Capture & Storage, Particle Technology
- N. TURRO • Supramolecular Photochemistry, Interface & Polymer Chemistry
- A.C. WEST • Electrochemical Engineering

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is Available

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New York, NY 10027  
(212) 854-4453



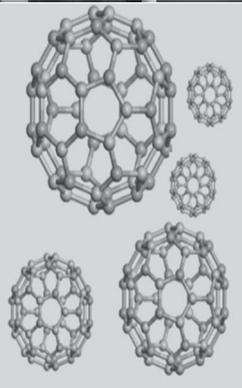
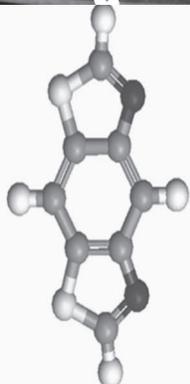
**WWW.CHEME.COLUMBIA.EDU**

# University of Connecticut

## Chemical Engineering Graduate Program

The Chemical Engineering Graduate Program within the Chemical, Materials & Biomolecular Engineering Department, at the University of Connecticut, offers many exciting research opportunities.

Our faculty members are superb on multiple levels and strive to provide students with an exceptional academic experience. Among our faculty you will find editors, inventors, world-renowned researchers and award-winning instructors.



**Alexander Agrios**, Northwestern University  
Applications of Nanoparticulate Semiconductors to Solar Energy Conversion

**George Bollas**, Aristotle University of Thessaloniki  
Simulation of Energy Processes, Property Models Development

**C. Barry Carter**, Oxford University  
Interfaces & Defects, Ceramics Materials, TEM, AFM, Energy

**Douglas Cooper**, University of Colorado  
Process Modeling & Control

**Chris Cornelius**, Virginia Polytechnic Institute and State University  
Structure, Property and Function of Polymers, Ionomers, Glasses and Composite Materials

**Russell Kunz**, Rensselaer Polytechnic Institute  
Fuel Cell Technology & Electrochemistry

**Cato Laurencin**, MIT M.D., Harvard Medical School  
Advanced Biomaterials, Tissue Engineering, Biodegradable Polymers, Nanotechnology

**Yu Lei**, University of California-Riverside  
Bionanotechnology, Bio/nanosensor, Bio/nanomaterials, Remediation

**Radenka Maric**, Kyoto University  
Nanostructure Materials, Polymers and Ceramic Processing

**Jeffrey McCutcheon**, Yale University  
Membrane Separations, Polymer Electrospinning, Forward Osmosis/Osmotic Power

**Ashish Mhadeshwar**, University of Delaware  
Modeling of Catalytic Fuel Processing, Deactivation & Emissions Reduction

**Trent Molter**, University of Connecticut  
Regenerative Fuel Cells, Hydrogen Production, Electrochemical Compressors, Fuel Cell Materials and Hydrogen Electrolyzers

**William Mustain**, Illinois Institute of Technology  
Proton Exchange Membrane Fuel Cells, Aerobic Biocathodes for ORR, Electrochemical Kinetics and Ionic Transport

**Mu-Ping Nieh**, University of Massachusetts, Amherst  
Self-assembly of Soft Materials & Structural Characterization of Polymer Thin Films and Polymer Hydrogels

**Richard Parnas**, UCLA  
Biodiesel Power Generation, PEM Fuel Cell, Polymer Gels & Filled Polymers

**Leslie Shor**, Rutgers, The State University of New Jersey  
Micro-scale Structures, Contaminant Fate & Transport in the Environment

**Prabhakar Singh**, University of Sheffield, England  
Solid Oxide Fuel Cells

**Ranjan Srivastava**, University of Maryland, College Park  
Systems Biology & Metabolic Engineering

**Steven Suib**, University of Illinois  
Inorganic Chemistry & Environmental Chemistry

**Yong Wang**, Duke University  
Nanomedicine & Drug Delivery

**Brian Willis**, MIT  
Nanotechnology, Molecular Electronics, Semiconductor Devices and Fuel Cells

### Research Centers

Booth Engineering Center for Advanced Technologies

Center for Clean Energy Engineering

Center for Environmental Sciences

Institute of Materials Science

### University of Connecticut

Chemical Engineering Program

191 Auditorium Road, Unit 3222

Storrs, CT 06269-3222

Phone: (860) 486-4020

Fax: (860) 486-2959

[www.cmbe.engr.uconn.edu](http://www.cmbe.engr.uconn.edu)

# UNIVERSITY OF DELAWARE

## Graduate Studies in Chemical Engineering

### ChE Faculty— Including 11 Named Professors

Maciek Antoniewicz  
Mark A. Barteau  
Antony Beris  
Douglas Buttrey  
Jingguang Chen  
David Colby  
Pam Cook  
Prasad Dhurjati  
Thomas Epps, III  
Eric Furst  
Feng Jiao  
Kelvin Lee  
Abraham Lenhoff  
Raul Lobo  
Tunde Ogunnaike  
Terry Papoutsakis  
Christopher Roberts  
Anne Robinson  
T.W. Frasier Russell  
Stanley Sandler  
Millicent Sullivan  
Dion Vlachos  
Norman Wagner  
Richard Wool

### RESEARCH AREAS:

Biomolecular, Cellular, and Protein  
Engineering  
Catalysis and Energy  
Metabolic Engineering  
Systems Biology  
Soft Materials, Colloids and Polymers  
Surface Science  
Nanotechnology  
Process Systems Engineering  
Green Engineering



The University of Delaware's central location on the eastern seaboard to New York, Washington, Philadelphia and Baltimore is convenient both culturally and to the greatest concentration of industrial & government research laboratories in the U.S.

**Chemical Engineering at Delaware is ranked, by all metrics, in the top 10 programs in the U.S. with world-wide reputation and reach. Built on a long and distinguished history, we are a vigorous and active leader in chemical engineering research and teaching. Our graduate students work with a talented and diverse faculty, and there is a correspondingly rich range of research and educational opportunities that are distinctive to Delaware.**

Centers and Programs provide unique environments & experiences for graduate students. These include:

**Delaware Biotechnology Institute (DBI)**  
**Center for Catalytic Science and Technology (CCST)**  
**Center for Molecular and Engineering Thermodynamics (CMET)**  
**Center for Neutron Science (CNS)**  
**Center for Composite Material (CCM)**  
**Chemistry-Biology Interface (CBI)**  
**Institute for Multi-Scale Modeling of Biological Interactions (IMMBI)**  
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The Technical University of Denmark (DTU) is a modern, internationally oriented technological university placed centrally in Scandinavia's Medicon Valley – one of the world's leading biotech clusters. It was founded in 1829 by H. C. Ørsted. The University has 6000 students preparing for their BSc or MSc degrees, 600 PhD students and takes 400 foreign students a year on English-taught courses. The DTU campus is located close to the city of Copenhagen, the capital of Denmark.



**Chemical Engineering areas of research and the research groups are:**

*Applied Thermodynamics, Aerosol Technology, Bio Process Engineering, Catalysis, Combustion Processes  
Emission Control, Enzyme technology, Membrane Technology, Polymer Chemistry & Technology  
Process Control, Product Engineering, Oil and Gas Production, Systems Engineering, Transport Phenomena*

**BioEng    PROCESS    CAPEC    CHEC    DPC    CERE**

The Department of Chemical Engineering (KT) is a leading research institution. The research results find application in biochemical processes, computer aided product and process engineering, energy, enhanced oil recovery, environment protection and pollution abatement, information technology, and products, formulations & materials.

The department has excellent experimental facilities serviced by a well-equipped workshop and well-trained technicians. The Hempel Student Innovation Laboratory is open for students' independent experimental work. The unit operations laboratory and pilot plants for distillation, reaction, evaporation, crystallization, etc. are used for both education and research. Visit us at <http://www.kt.dtu.dk/English.aspx>.



The starting point for general information about MSc studies at DTU is:  
<http://www.dtu.dk/msc>

**Graduate programs at Department of Chemical and Biochemical Engineering:**

**Chemical and Biochemical Engineering**

<http://www.kt.dtu.dk/cbe>

**Stig Wedel** sw@kt.dtu.dk

**Elite track in Chemical and Biochemical Engineering**

<http://www.kt.dtu.dk/elite>

**John Woodley** jw@kt.dtu.dk

**Petroleum Engineering**

<http://www.cere.kt.dtu.dk/petroleum/>

**Alexander Shapiro** ash@kt.dtu.dk

**Advanced and Applied Chemistry**

<http://www.kt.dtu.dk/aachemistry>

**Georgios Kontogeorgis** gk@kt.dtu.dk

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**Dept. Chemical and Biochemical Engineering**



# Drexel University Department of Chemical and Biological Engineering

[www.chemeng.drexel.edu/](http://www.chemeng.drexel.edu/)



## Faculty

### **Cameron F. Abrams**

PhD, University of California-Berkeley  
multiscale molecular simulations, polymer thermodynamics, molecular and cellular biophysics

### **Jason B. Baxter**

PhD, University of California-Santa Barbara  
solar cells, nanowires

### **Richard A. Cairncross**

PhD, University of Minnesota  
transport in polymers, biodegradable polymers, transport modeling, coatings, renewable energy

### **Nily R. Dan**

PhD, University of Minnesota  
gene and drug delivery, polymer nano-composites, complex fluids

### **Yossef A. Elabd**

PhD, Johns Hopkins University  
fuel cells, polymer membranes, diffusion in polymers, electrocatalysts

### **Vibha Kalra**

PhD, Cornell University  
polymer nano-composites, multi-scale simulations

### **Kenneth K.S. Lau**

PhD, Massachusetts Institute of Technology  
surface science, nanotechnology, polymer thin films and coatings, chemical vapor deposition

### **Anthony M. Lowman**

PhD, Purdue University  
biomaterials, drug delivery, hydrogels

### **Raj Mutharasan**

PhD, Drexel University  
biochemical engineering, cellular metabolism in bioreactors, biosensors

### **Giuseppe R. Palmese, Head**

PhD, University of Delaware  
reacting polymer systems, nanostructured polymers, materials from renewable sources, composites and interfaces

### **Masoud Soroush**

PhD, University of Michigan  
process systems engineering, polymer engineering, modeling simulations

### **Steven P. Wrenn**

PhD, University of Delaware  
biomedical engineering, biological colloids, intercellular phase separation and mass transfer

## What does Drexel offer?

### Graduate Research

Drug Delivery  
Fuel Cells  
Solar Cells  
Polymers  
Molecular Simulations  
Biomaterials  
Biosensors  
Nanotechnology

### Degree Options

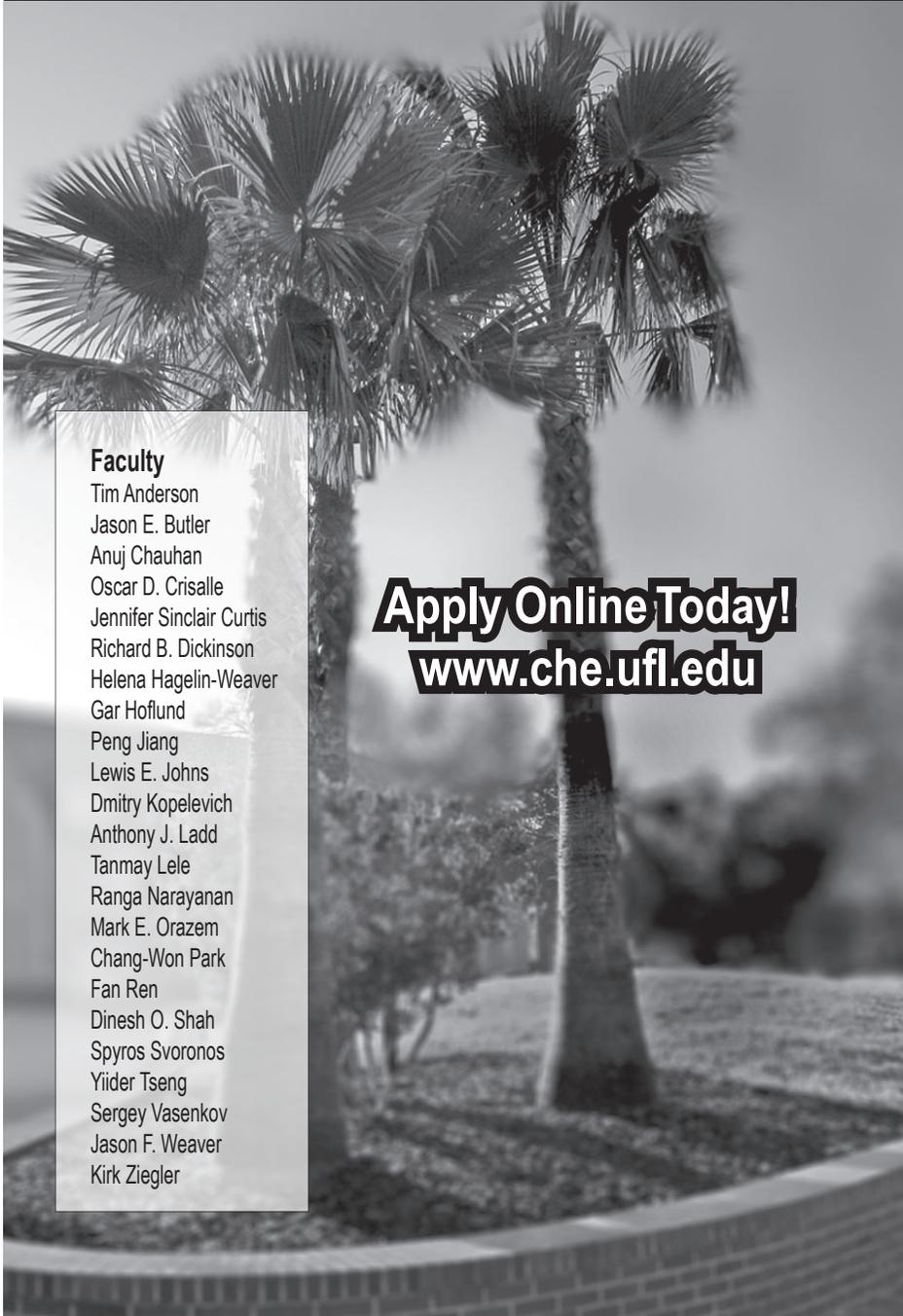
BS  
BS/MS (5 yrs)  
BS/Phd  
MS  
PhD  
BS/MD (7 yrs)

Drexel University is conveniently located in downtown Philadelphia with easy access to numerous cultural centers, transportation, and major pharmaceutical, chemical, and petroleum companies.

For more information about applying to one of our programs, please contact Professor Jason Baxter at 215-895-2240 or [jbaxter@drexel.edu](mailto:jbaxter@drexel.edu)



*Chemical Engineering Graduate Studies at the*  
**University of Florida**



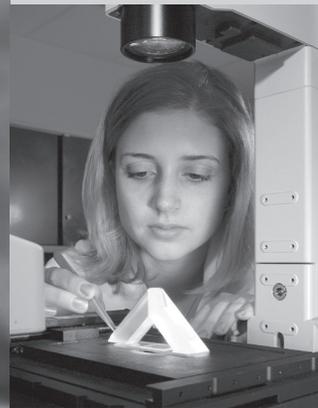
**Faculty**

Tim Anderson  
Jason E. Butler  
Anuj Chauhan  
Oscar D. Crisalle  
Jennifer Sinclair Curtis  
Richard B. Dickinson  
Helena Hagelin-Weaver  
Gar Hoflund  
Peng Jiang  
Lewis E. Johns  
Dmitry Kopelevich  
Anthony J. Ladd  
Tanmay Lele  
Ranga Narayanan  
Mark E. Orazem  
Chang-Won Park  
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Dinesh O. Shah  
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(C&E News, December 15, 2008)





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### Faculty

P.A. Jennings, Ph.D., Department Head  
J.E. Whitlow, Ph.D.  
M.M. Tomadakis, Ph.D.  
M.E. Pozo de Fernandez, Ph.D.  
J.R. Brenner, Ph.D.  
J. Thomas, Ph.D.  
R.G. Basile, Ph.D.



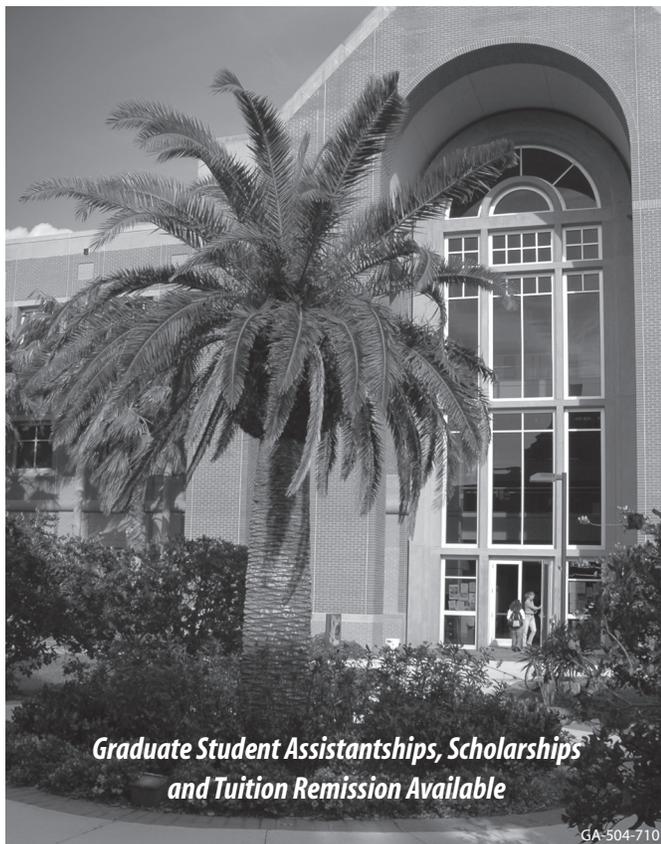
### Research Interests

Spacecraft Technology  
In-Situ Resource Utilization  
Alternative Energy Sources  
Materials Science  
Membrane Technology

### Research Partners

NASA  
Department of Energy  
Department of Defense  
Florida Solar Energy Center\*  
Florida Department of Agriculture  
*\*Doctoral fellowship sponsor*

For more information, contact  
***Florida Institute of Technology***  
College of Engineering  
Department of Chemical Engineering  
150 W. University Blvd.  
Melbourne, FL 32901-6975  
(321) 674-8068  
<http://coe.fit.edu/chemical>



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of Engineering

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than 70 National  
and International  
Awards

**DEGREES:**

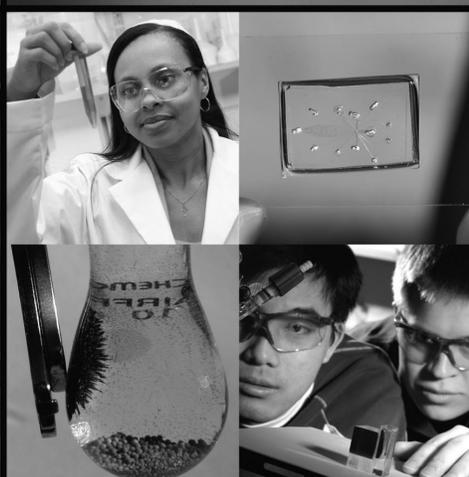
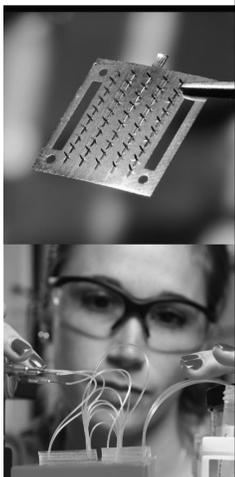
Chemical  
Engineering

Bioengineering

Paper Science  
and Engineering



# RESEARCH EXCELLENCE



## Georgia Institute of Technology

**CONTACT INFORMATION:**

Dr. Aryn Teja, Associate Chair for Graduate Studies  
School of Chemical & Biomolecular Engineering  
Georgia Institute of Technology  
Atlanta, Georgia 30332-0100  
[grad.info@chbe.gatech.edu](mailto:grad.info@chbe.gatech.edu)  
404.894.1838 • 404.894.2866 fax

**KEY RESEARCH  
AREAS:**

**Biotechnology • Energy • Systems • Materials/Nanotechnology**

Catalysis, Reaction Kinetics, Complex Fluids, Microelectronics, Polymers, Microfluidics, Pulp & Paper, Separations, Thermodynamics, MEMS, Environmental Science, CO<sub>2</sub> Capture, Biomedicine, Solar Energy, Cancer Diagnostics & Therapeutics, Biofuels, Air Quality, Modeling, Process Synthesis and Control, Optimization, Bioinformatics

## 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	Multi-Phase Flows
Alternative Energy	Nanotechnology
Biomolecular Engineering	Plasma Processing
Catalysis	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](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/>



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Write: University of Houston  
Chemical and Biomolecular Engineering  
Graduate Admission  
S222 Engineering Building 1  
Houston, TX 77204-404

# 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  
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**Ying Liu**, Assistant Professor  
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**G. Ali Mansoori**, Professor  
Ph.D., University of Oklahoma, 1969  
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**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  
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**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., Illinois Institute of Technology, 2000  
Email: sah@uic.edu

**Cynthia J. Jameson**, Professor Emeritus  
Ph.D., University of Illinois at  
Chicago-Urbana/Champaign, 1963  
Email: cjames@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 functional 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, Microvasculature, 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

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## Chemical and Biomolecular Engineering

The combination of distinguished faculty, outstanding facilities, and a diversity of research interests results in exceptional opportunities for graduate education at the University of Illinois at Urbana-Champaign. The Chemical and Biomolecular Engineering Department offers graduate programs leading to the M.S. and Ph.D. degrees.

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**Or write to:**

Department of Chemical and Biomolecular Engineering  
University of Illinois at Urbana-Champaign  
114 Roger Adams Laboratory, Box C-3  
600 South Mathews Avenue  
Urbana, IL 61801-3602



### FACULTY

**Richard D. Braatz**

Multiscale Systems and Control

**Steve Granick**

Soft Materials, Nanoscience, Colloids, Imaging

**William S. Hammack**

Public Outreach and Engineering Literacy

**Brendan A. Harley**

Biomaterials and Tissue Engineering

**Jonathan J. L. Higdon**

Fluid Mechanics and Computational Algorithms

**Paul J. A. Kenis**

Microchemical Systems: Microreactors, Microfuel Cells, and Microfluidic Tools

**Hyun Joon Kong**

Design of Bioinspired Materials, Engineering of Stem Cell Niches, Tissue Engineering

**Mary L. Kraft**

Surface Analysis and Biomembranes

**Deborah E. Leckband**

Bioengineering and Biophysics

**Jennifer A. Lewis**

Materials Assembly, Complex Fluids, and Mesoscale Fabrication

**Richard I. Masel**

Microchemical Systems, Micro Fuel Cells, Sensors

**Daniel W. Pack**

Biomolecular Engineering and Biotechnology

**Nathan D. Price**

Computational and Systems Biology

**Christopher V. Rao**

Computational Biology and Cellular Engineering

**Charles M. Schroeder**

Single Molecule Biology, Biophysics and Biomolecular Engineering

**Kenneth S. Schweizer**

Macromolecular, Colloidal and Complex Fluid Theory

**Edmund G. Seebauer**

Microelectronics Processing and Nanotechnology

**Mark A. Shannon**

MEMS, NEMS, and Water Purification

**Huimin Zhao**

Molecular Bioengineering and Biotechnology

**Charles F. Zukoski**

Colloid and Interfacial Science

## 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
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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 biochem-  
ical 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 envi-  
ronmental interfaces/  
Heterogeneous atmospheric  
chemistry/Applications and  
implications of nanosci-  
ence 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/Baculo-  
virus biopesticides*



**Eric E. Nuxoll**  
U. of Minnesota 2003  
*Controlled release/  
microfabrication/  
drug delivery*



**Tonya L. Peeples**  
Johns Hopkins 1994  
*Extremophile biocataly-  
sis/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/Immuno-  
cancer therapy/Nano  
and microtechnology*



**Alec B. Scranton**  
Purdue U. 1990  
*Photopolymerization/  
Reversible emulsifiers/  
Polymerization kinetics*



**Charles O. Stanier**  
Carnegie Mellon  
University 2003  
*Air pollution chemis-  
try, measurement, and  
modeling/Aerosols*



**Venkiteswaran  
Subramanian**  
Indian Institute of Science  
1978  
*Biocatalysis/Metabolism/  
Gene expression/  
Fermentation/Protein  
purification/Biotechnology*



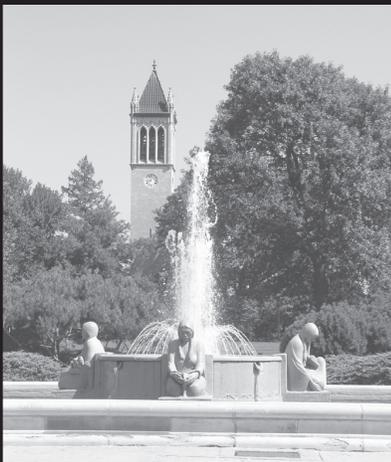
**For information  
and application:**  
**THE UNIVERSITY  
OF IOWA**

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/

# IOWA STATE UNIVERSITY

## OF SCIENCE AND TECHNOLOGY



Iowa State University's Department of Chemical and Biological Engineering offers excellent programs for graduate research and education. Our cutting-edge research crosses traditional disciplinary lines and provides exceptional opportunities for graduate students. Our diverse faculty are leaders in their fields and have won national and international recognition for both research and education, our facilities (laboratories, instrumentation, and computing) are state of the art, and our financial resources give graduate students the support they need not just to succeed, but to excel. Our campus houses several interdisciplinary research centers, including the Ames

Laboratory (a USDOE laboratory focused on materials research), an NSF Engineering Research Center on chemicals from biorenewables, the Plant Sciences Institute, the Office of Biotechnology, and the Bioeconomy Institute.

The department offers ME, MS, and PhD degrees in chemical engineering. Students with undergraduate degrees in chemical engineering or related fields can be admitted to the program. We offer full financial support with tuition coverage and competitive stipends to all our MS and PhD students. In addition, we offer several competitive fellowships.

## Faculty

### Robert C. Brown

PhD, Michigan State University  
*Biorenewable resources for energy*

### Aaron R. Clapp

PhD, University of Florida  
*Colloidal and interfacial phenomena*

### Eric W. Cochran

PhD, University of Minnesota  
*Self-assembled polymers*

### Rodney O. Fox

PhD, Kansas State University  
*Computational fluid dynamics and reaction engineering*

### Charles E. Glatz

PhD, University of Wisconsin  
*Bioprocessing and bioseparations*

### Kurt R. Hebert

PhD, University of Illinois  
*Corrosion and electrochemical engineering*

### James C. Hill

PhD, University of Washington  
*Turbulence and computational fluid dynamics*

### Andrew C. Hillier

PhD, University of Minnesota  
*Interfacial engineering and electrochemistry*

### Laura Jarboe

PhD, University of California-LA  
*Biorenewables production by metabolic engineering*

### Kenneth R. Jolls

PhD, University of Illinois  
*Chemical thermodynamics and separations*

### Monica H. Lamm

PhD, North Carolina State University  
*Molecular simulations of advanced materials*

### Surya K. Mallapragada

PhD, Purdue University  
*Tissue engineering and drug delivery*

### Balaji Narasimhan

PhD, Purdue University  
*Biomaterials and drug delivery*

### Jennifer O'Donnell

PhD, University of Delaware  
*Amphiphile self-assembly and controlled polymerizations*

### Michael G. Olsen

PhD, University of Illinois  
*Experimental fluid mechanics and turbulence*

### Peter J. Reilly

PhD, University of Pennsylvania  
*Enzyme engineering and bioinformatics*

### Derrick K. Rollins

PhD, Ohio State University  
*Statistical process control*

### Ian Schneider

PhD, North Carolina State University  
*Cell migration and mechanotransduction*

### Brent H. Shanks

PhD, California Institute of Technology  
*Heterogeneous catalysis and biorenewables*

### Jacqueline V. Shanks

PhD, California Institute of Technology  
*Metabolic engineering and plant biotechnology*

### R. Dennis Vigil

PhD, University of Michigan  
*Transport phenomena and reaction engineering in multiphase systems*



## FOR MORE INFORMATION

Graduate Admissions Committee  
**Department of Chemical and Biological Engineering**  
Iowa State University  
Ames, Iowa 50011  
**515 294-7643**  
Fax: 515 294-2689  
[chemengr@iastate.edu](mailto:chemengr@iastate.edu)  
[www.cbe.iastate.edu](http://www.cbe.iastate.edu)

Iowa State University does not discriminate on the basis of race, color, age, religion, national origin, sexual orientation, sex, marital status, disability, or status as a U.S. Vietnam Era Veteran. Any persons having inquiries concerning this may contact the Director of Equal Opportunity and Diversity, 3680 Beardshear Hall, 515 294-7612. ECM 09546

**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. 15<sup>th</sup> Street, Room 4132  
Lawrence, KS 66045-7609

phone: 785-864-2900  
fax: 785-864-4967  
e-mail: [cpegrad@ku.edu](mailto:cpegrad@ku.edu)

# Study chemical engineering's hottest topics at one of the top U.S. research universities.

Kansas State University is indexed in the Carnegie Foundation's list of top 96 U.S. universities with "very high research activity." Graduate students perform research in areas like bio/nanotechnology, reaction engineering, materials science and transport phenomena.

K-State offers modern, well-equipped laboratories and expert faculty on a campus nationally recognized for its great community relationship. The department of chemical engineering offers M.S. and Ph.D. degrees in chemical engineering and the interdisciplinary areas of bio-based materials science and engineering, food science, environmental engineering and materials science. A certificate in air quality is also available.



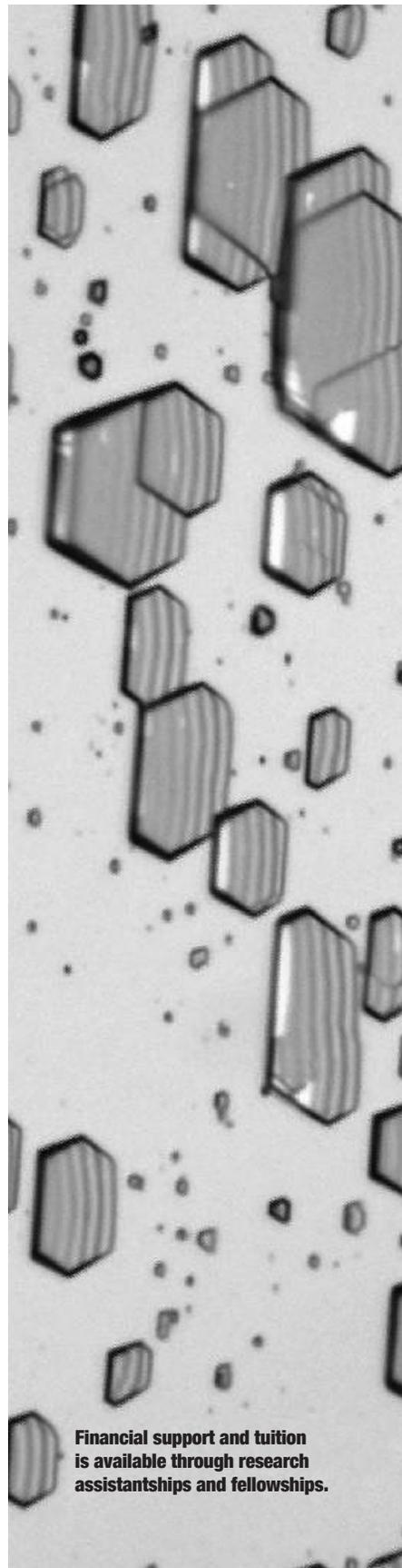
## Faculty, Research Areas

- ▶ Jennifer L. Anthony, advanced materials, molecular sieves, environmental applications, ionic liquids
- ▶ Vikas Berry, graphene technologies, bionanotechnology, nanoelectronics and sensors
- ▶ James H. Edgar (head), crystal growth, semiconductor processing and materials characterization
- ▶ Larry E. Erickson, environmental engineering, biochemical engineering, biological waste treatment process design and synthesis
- ▶ L.T. Fan, process systems engineering including process synthesis and control, chemical reaction engineering, particle technology
- ▶ Larry A. Glasgow, transport phenomena, bubbles, droplets and particles in turbulent flows, coagulation and flocculation
- ▶ Keith L. Hohn, catalysis and reaction engineering, nanoparticle catalysts and biomass conversion
- ▶ Peter Pfromm, polymers in membrane separations and surface science
- ▶ Mary E. Rezac, polymer science, membrane separation processes and their applications to biological systems, environmental control and novel materials
- ▶ John R. Schlup, biobased industrial products, applied spectroscopy, thermal analysis and intelligent processing of materials

## Our instrumental capabilities include:

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- ▶ Fourier-transform infrared spectrometry
- ▶ Chemical vapor deposition reactors
- ▶ Electrodialysis
- ▶ Fermentors
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- ▶ Gas and liquid chromatography
- ▶ Mass spectrometry
- ▶ High-speed videography
- ▶ Gas adsorption analysis
- ▶ Catalyst preparation equipment
- ▶ Membrane permeation systems
- ▶ Ultra-high temperature furnaces
- ▶ More

[www.che.ksu.edu](http://www.che.ksu.edu)



Financial support and tuition is available through research assistantships and fellowships.

**Key Research Areas:**

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- Biopharmaceutical and Biocellular Engineering
- Energy Resources and Alternative Energy
  - Environmental Engineering
  - Interfacial Engineering
- Materials Synthesis • Nanomaterials
  - Polymers and Membranes
  - Supercritical Fluids Processing



*The CME Department offers graduate programs leading to the M.S. and Ph.D. degrees in both chemical and materials engineering. The combination of these disciplines in a single department fosters collaboration among faculty and a strong interdisciplinary environment. Our faculty and graduate students pursue research projects that encompass a broad range of chemical engineering endeavor, and that include strong interactions with researchers in Agriculture, Chemistry, Medicine and Pharmacy.*



**Chemical Engineering Faculty**

- D. Kalika, Chair • *University of California, Berkeley*
- K. Anderson • *Carnegie-Mellon University*
- R. Andrews • *University of Kentucky*
- D. Bhattacharyya • *Illinois Institute of Technology*
- T. Dziubla • *Drexel University*
- E. Grulke • *Ohio State University*
- J. Z. Hilt • *University of Texas*
- S. Hutcheson • *Texas Tech University*
- R. Kermode • *Northwestern University*
- B. Knutson • *Georgia Institute of Technology*
- S. Rankin • *University of Minnesota*
- A. Ray • *Clarkson University*
- J. Seay • *Auburn University*
- D. Silverstein • *Vanderbilt University*
- J. Smart • *University of Texas*
- T. Tsang • *University of Texas*

**Materials Engineering Faculty**

- T. J. Balk • *Johns Hopkins University*
- M. Beck • *Northwestern University*
- Y. T. Cheng • *California Institute of Technology*
- R. Eitel • *Pennsylvania State University*
- B. Hinds • *Northwestern University*
- F. Yang • *University of Rochester*
- T. Zhai • *University of Oxford*

**For more information contact:**

Director of Graduate Studies • Department of Chemical and Materials Engineering • 177 F. Paul Anderson Tower • University of Kentucky • Lexington, KY 40506-0046 • Phone: 859.257.8028



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Polymer Science & Engineering • Process Modeling & Control  
Two-Phase Flow & Heat Transfer*

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and Polymer Science and Engineering*

## OUR FACULTY

**Bryan W. Berger**, *University of Delaware*

membrane biophysics • protein engineering • surfactant science  
• signal transduction

**Philip A. Blythe**, *University of Manchester*

fluid mechanics • heat transfer • applied mathematics

**Hugo S. Caram**, *University of Minnesota*

high temperature processes and materials • environmental  
processes • reaction engineering

**Manoj K. Chaudhury**, *SUNY - Buffalo*

adhesion • thin films • surface chemistry

**Mohamed S. El-Aasser**, *McGill University*

polymer colloids and films • emulsion copolymerization •  
polymer synthesis and characterization

**Alice P. Gast**, *Princeton University*

complex fluids • colloids • proteins • interfaces

**James F. Gilchrist**, *Northwestern University*

particle self-organization • mixing • microfluidics

**Vincent G. Grassi II**, *Lehigh University*

process systems engineering

**Lori Herz**, *Rutgers University*

cell culture and fermentation • pharmaceutical process  
development and manufacturing

**James T. Hsu**, *Northwestern University*

bioseparation • applied recombinant DNA technology

**Anand Jagota**, *Cornell University*

biomimetics • mechanics • adhesion • biomolecule-materials  
interactions

**Andrew Klein**, *North Carolina State University*

emulsion polymerization • colloidal and surface effects in  
polymerization

**Mayuresh V. Kothare**, *California Institute of Technology*

model predictive control • constrained control • microchemical  
systems

**Ian J. Laurenzi**, *University of Pennsylvania*

chemical kinetics in small systems • biochemical informatics •  
aggregation phenomena

**William L. Luyben**, *University of Delaware*

process design and control • distillation

**Anthony J. McHugh**, *University of Delaware*

polymer rheology and rheo-optics • polymer processing and  
modeling • membrane formation • drug delivery

**Jeetain Mittal**, *University of Texas*

protein folding • macromolecular crowding • hydrophobic  
effects • nanoscale transport

**Susan F. Perry**, *Pennsylvania State University*

cell adhesion and migration • cellular biomechanics

**Arup K. Sengupta**, *University of Houston*

use of adsorbents • ion exchange • reactive polymers •  
membranes in environmental pollution

**Cesar A. Silebi**, *Lehigh University*

separation of colloidal particles • electrophoresis • mass  
transfer

**Shivaji Sircar**, *University of Pennsylvania*

adsorption • gas and liquid separation

**Mark A. Snyder**, *University of Delaware*

inorganic nanoparticles and porous thin films •  
membrane separations • multiscale modeling

**Kemal Tuzla**, *Istanbul Technical University*

heat transfer • two-phase flows • fluidization • thermal energy  
storage

**Israel E. Wachs**, *Stanford University*

materials characterization • surface chemistry • heterogeneous  
catalysis • environmental catalysis

*An application and additional information  
may be obtained by writing to:*

*Dr. James T. Hsu, Chair - Graduate Committee*

*Department of Chemical Engineering, Lehigh University • 111 Research Drive, Iacocca Hall • Bethlehem, PA 18015*

*Fax: (610) 758-5057 • Email: [incheqs@lehigh.edu](mailto:incheqs@lehigh.edu) • Web: [www.che.lehigh.edu](http://www.che.lehigh.edu)*



### 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

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### 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/Asst. 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/Asst. 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/Asst. 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 nanopores 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:*

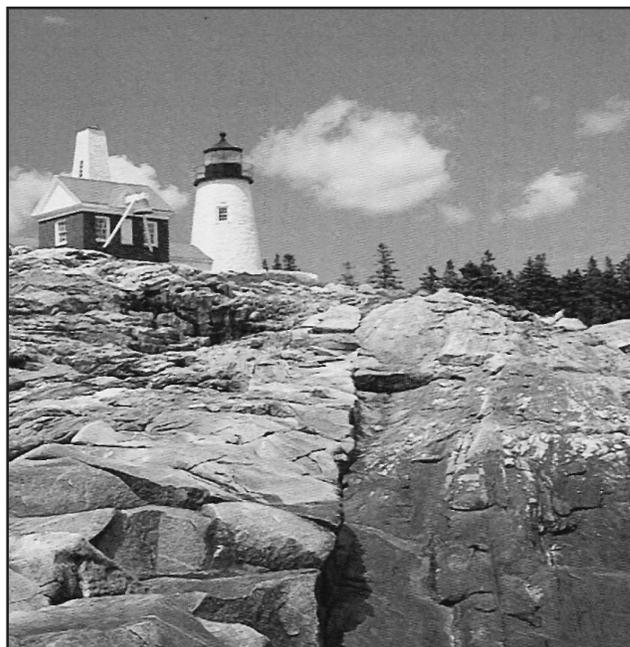
Graduate Coordinator,

Department of Chemical and Biological Engineering

University of Maine, Orono, ME 04469

call 207 581-2277 • e-mail [gradinfo@umche.maine.edu](mailto:gradinfo@umche.maine.edu) or

[bousfld@maine.edu](mailto:bousfld@maine.edu) • visit [www.umche.maine.edu](http://www.umche.maine.edu)



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*For information and application form, write to*

**Graduate Program Director  
Chemical Engineering Department  
Manhattan College  
Riverdale, NY 10471  
chmldept@manhattan.edu**

<http://www.engineering.manhattan.edu>

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Chemical  
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northwest section of  
New York City.*

# UMBC

AN HONORS  
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IN MARYLAND

# CHEMICAL & BIOCHEMICAL ENGINEERING



## FACULTY RESEARCH AREAS:

**Biomaterials  
Engineering**

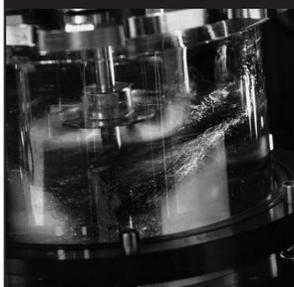
**Bioprocess  
Engineering**

**Cellular  
Engineering**

**Engineering  
Education  
& Outreach**

**Sensor  
Technology**

**Systems  
Biology &  
Functional  
Genomics**



## APPLY FOR FREE!

The Department of Chemical and Biochemical Engineering at UMBC is pleased to offer citizens and permanent residents of the United States and Canada, and students receiving degrees from U.S. and Canadian institutions, the opportunity to apply for admission to the Ph.D. program in Chemical & Biochemical Engineering without admission fees. Details are available on our Web site ([www.umbc.edu/cbe](http://www.umbc.edu/cbe)).

### PROGRAM DESCRIPTION

Students pursuing advanced studies in the Department of Chemical and Biochemical Engineering at UMBC explore fundamental concepts in biochemical, biomedical and bioprocess engineering, with faculty at the leading-edge of engineering research. The department offers graduate programs leading to B.S./M.S., M.S. and Ph.D. degrees. These graduate programs provide students with the opportunity to play an active role in breakthrough research and specific projects cover a wide range of areas including: fermentation, cell culture, downstream processing, cellular and tissue engineering as well as mathematical modeling.

### DEGREES OFFERED

M.S. (thesis and non-thesis), Ph.D.

Accelerated Bachelor's/Master's

Post-Baccalaureate Certificate in Biochemical Regulatory Engineering

### FACILITIES AND SPECIAL RESOURCES

The program's research facilities include state-of-the-art laboratories in the Engineering Building and at the Technology Research Center. These facilities are extensively equipped with modern fermentation, cell culture, separations, protein structure and materials characterization, biomaterials synthesis and other analytical equipment. In addition, campus core facilities in areas such as microscopy and mass spectrometry provide students opportunities for hands-on exposure to cutting edge analytical techniques and equipment.

### LOCATION

UMBC is a suburban campus, located in the Baltimore-Washington corridor, with easy access to both metropolitan areas. A number of government research facilities such as NIH, FDA, USDA, NSA, and a large number of biotechnology companies are located nearby and provide excellent opportunities for research interactions.

### FACULTY

BAYLES, TARYN, Ph.D., University of Pittsburgh; Engineering education and outreach, transport phenomena

CASTELLANOS, MARIAJOSE, Ph.D., Cornell University; Biocomplexity, modeling of biological systems

FREY, DOUGLAS, Ph.D., University of California, Berkeley; Chromatographic separations, electrophoresis

GOOD, THERESA, Ph.D., University of Wisconsin-Madison; Cellular engineering, protein aggregation and disease, biomedical engineering

LEACH, JENNIE, Ph.D., University of Texas at Austin; Biomaterials, tissue engineering

MARTEN, MARK, Ph.D., Purdue University; Systems biology, proteomics and genomics, bioprocessing

MOREIRA, ANTONIO R., Ph.D., University of Pennsylvania; Regulatory/GMP issues, scale up, downstream processing, product comparability

RAO, GOVIND, Ph.D., Drexel University; Fluorescence-based sensors and instrumentation, fermentation, cell culture

ROSS, JULIA, Ph.D., CHAIR; Rice University; Cell and tissue engineering, cell adhesion in microbial infection, thrombosis

### Research Associate Professors

KOSTOV, YORDAN, Ph.D., Bulgarian Academy of Sciences; Low-cost optical sensors, instrumentation development, biomaterials

TOLOSA, LEAH, Ph.D., University of Connecticut, Storrs; Fluorescence based sensors, protein engineering, biomedical diagnostics, molecular switches

### Research Assistant Professor

GE, XUDONG, Ph.D., UMBC; Sensor matrix development, dialysis based sensor

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### FACULTY

**RAYMOND A. ADOMAITIS**  
Systems modeling/simulation;  
semiconductor materials manufacturing.

**MIKHAIL ANISIMOV**  
Mesoscopic and nanoscale  
thermodynamics; critical phenomena;  
phase transitions in soft matter.

**RICHARD V. CALABRESE**  
Multiphase flow, turbulence and mixing.

**KYU YONG CHOI**  
Polymer reaction engineering and polymer  
nanomaterials.

**PANAGIOTIS DIMITRAKOPOULOS**  
Computational fluid dynamics, bio/micro-  
fluidics, biophysics and numerical analysis.

**SHERYL H. EHRMAN**  
Aerosol science; particle technology;  
air pollution.

**JEFFERY KLAUDA**  
Cell membrane biophysics;  
thermodynamics; molecular simulations.

**SRINIVASA R. RAGHAVAN**  
Complex fluids; polymeric and  
biomolecular self-assembly; soft  
nanostructures.

**GANESH SRIRAM**  
Systems biology; metabolic engineering;  
biorenewable fuel; genetically inherited  
metabolic disorders.

**CHUNSHENG WANG**  
Energy conversion for fuel cells; energy  
storage systems; sensors; electrochemis-  
try; nanostructured materials.

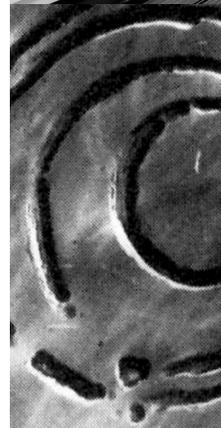
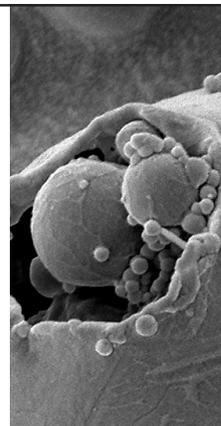
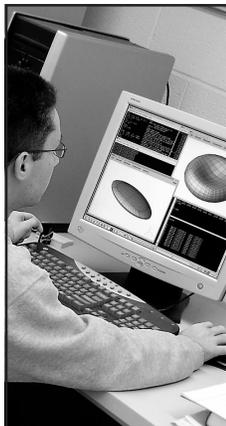
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University of Massachusetts  
Amherst, MA 01003-9303  
Email: [chegradprog@ecs.umass.edu](mailto:chegradprog@ecs.umass.edu)



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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...
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- **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 ...

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# Chemical Engineering



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- T. M. QUINN**, (MIT) Canada Research Chair  
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- N. TUFENKJI**, Canada Research Chair (Yale)  
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- V. YARGEAU**, (Sherbrooke)  
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- ◆ **Process Systems Engineering:** Multivariate statistical methods, computer process control, optimization  
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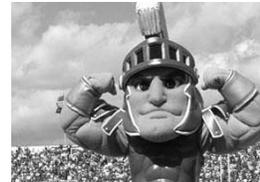
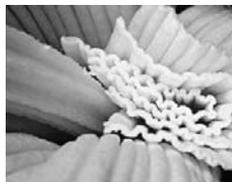
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The Crucible, outside of Amundson Hall

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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 pacesetter 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.

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***For details contact:***

Coordinator, Academic Programs  
Department of Chemical Engineering  
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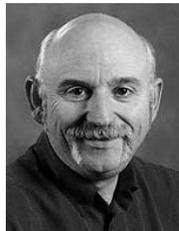
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## Graduate Studies at Chemical and Biological Engineering

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MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

### Chemical and Biological Engineering

Graduate Studies  
143 Schrenk Hall  
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Rolla, MO 65409-1230

Web: [chemeng.mst.edu](http://chemeng.mst.edu)  
Email: [mstchemengr@mst.edu](mailto:mstchemengr@mst.edu)



researching complex *chemical* and *biomolecular*  
*engineering solutions for the future* of health care

*The Department of Chemical & Biomolecular Engineering at the University of Nebraska–Lincoln ranks 14<sup>th</sup> among 158 chemical engineering graduate programs in the United States in research and development expenditures.\**

### Department of Chemical & Biomolecular Engineering NIH Grants \*\*

#### Sponsored by the NIH-National Health, Lung & Blood Institute

cGMP Recombinant FIX for IV & Oral Hemophilia B Therapy  
William Velander & Kevin Van Cott, \$10,462,370, 9/6/2005-8/31/2011, R01 HL078944

#### Sponsored by the NIH-National Center for Research Resources

A Rational Design of a Platform for de novo Gene Synthesis  
Hendrik Viljoen, \$1,369,548, 5/1/2007-8/31/2011, R21 RR022860

A Rational Design of a Platform for de novo Gene Synthesis  
Anuradha Subramanian, \$1,681,105, 4/1/2006-3/31/2011, R21 RR022860

Design & Evaluation of Ultrasound Stimulation-Aided Bioreactor Configurations  
Anuradha Subramanian, \$533,941, 9/7/2009-8/31/2011, R21 RR024437

#### Sponsored by the NIH-National Institute of Biomedical Imaging & Bioengineering

Nanodevice for Digital Imaging of Palpable Structure at Human-Finger Resolution for Clinical Breast Examination  
Ravi Saraf, \$377,552, 2/26/2008-1/31/2011, R21 EB008520

**Additional grants from the National Science Foundation, the United States Army and other granting institutions.**

\*Source: National Science Foundation/Division of Science Resources Statistics, FY 2008, Table 62. R&D expenditures in engineering subfields at universities and colleges, ranked by all engineering R&D expenditures in subfields. \*\*Data compiled June, 2010

### Research Areas

- Biomolecular Engineering
- Tissue Engineering
- Nanotechnology
- Biomaterials
- Biotechnology
- Biocatalysis
- Molecular Medicine

### Contact Us

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Fax: (402) 472-6989  
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# The Program

The department offers graduate programs leading to both the Master of Science and Doctor of Philosophy degrees. Exciting opportunities exist for interdisciplinary research. Faculty conduct research in a number of areas including:

- Polymer science/ engineering
- Membrane technology
- Hazardous waste treatment
- Particle technology
- Pharmaceutical engineering
- Nanotechnology



New Jersey's Science &  
Technology University

## Chemical, Biological & Pharmaceutical Engineering

### The Faculty:

---

- P. Armenante:** University of Virginia  
**B. Baltzis:** University of Minnesota  
**R. Barat:** Massachusetts Institute of Technology  
**E. Bilgili:** Illinois Institute of Technology  
**R. Dave:** Utah State University  
**E. Dreizin:** Odessa University, Ukraine  
**C. Gogos:** Princeton University  
**T. Greenstein:** New York University  
**D. Hanesian:** Cornell University  
**K. Hyun:** University of Missouri-Columbia  
**B. Khusid:** Heat and Mass Transfer Inst., Minsk USSR  
**H. Kimmel:** City University of New York  
**N. Loney:** New Jersey Institute of Technology  
**A. Perna:** University of Connecticut  
**R. Pfeffer:** (Emeritus); New York University  
**D. Sebastian:** Stevens Institute of Technology  
**L. Simon:** Colorado State University  
**K. Sirkar:** University of Illinois-Urbana  
**R. Tomkins:** University of London (UK)  
**X. Wang:** Virginia Tech  
**M. Xanthos:** University of Toronto (Canada)  
**M. Young:** Stevens Institute of Technology

### For further information contact:

---

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New Jersey Institute of Technology  
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Phone: (973) 596-5656 Fax: (973) 596-8436  
E-mail: Norman.Loney@adm.njit.edu, tomkinsr@adm.njit.edu

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## THE FACES OF THE CHEMICAL ENGINEERS IN THE 21<sup>ST</sup> CENTURY

### The University of New Mexico



We are the future of chemical engineering! Chemical engineers in the 21<sup>st</sup> 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

Plamen Atanassov  
C. Jeffrey Brinker  
Heather Canavan  
Joseph L. Cecchi  
Eva Chi  
John G. Curro  
Abhaya K. Datye  
Elizabeth L. Dirk  
Julia E. Fulghum  
Steven Graves  
Sang M. Han  
Ronald E. Loehman  
Dimitar Petsev  
Timothy L. Ward  
David G. Whitten

#### Research Areas

- Electroanalytical Chemistry, Biomedical Engineering
- Ceramics, Sol-Gel Processing, Self-assembled Nanostructures
- Stimulus-responsive materials, cell/surface interactions, Biomedical Engineering
- Semiconductor Manufacturing Technology, Plasma Etching and Deposition
- Protein interfacial dynamics, protein aggregation, protein misfolding diseases
- Polymer Theory, Computational Modeling
- Catalysis, Interfaces, Advanced Materials
- Biomaterials, Tissue Engineering
- Surface Characterization, 3-D Materials Characterization
- Biomolecular Assemblies, Protease Mechanisms, Flow Cytometry
- Semiconductor Manufacturing Technology, Plasma Etching and Deposition
- Glass-Metal and Ceramic-Metal Bonding and Interfacial Reactions
- Complex fluids, Nanoscience, Electrokinetic phenomena
- Aerosol Materials Synthesis, Inorganic Membranes
- 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

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# 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*

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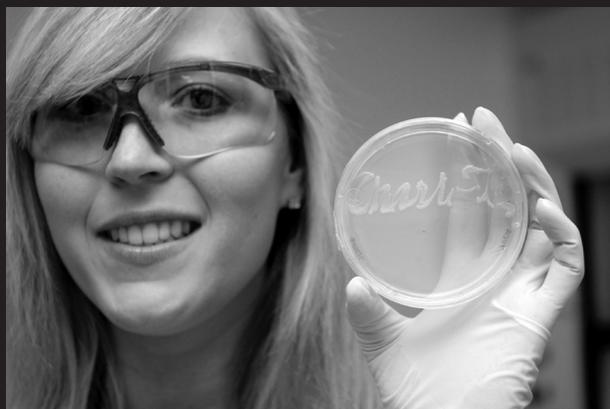
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Telephone • (575) 646-1214    E-mail • [chemeng@nmsu.edu](mailto:chemeng@nmsu.edu)  
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**NC STATE UNIVERSITY**

## Department of Chemical and Biomolecular Engineering



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### The Department

- # 2 in research expenditures among CBE departments in the US (2008, C&EN)
- # 14 in PhD graduates (2008, ACS)
- # 6 in BS graduates (2008, ASEE)

Our Department is located in Engineering Building I – a 161,217-square-foot teaching and research facility located on NC State's Centennial Campus. The EBI classrooms, atrium, and student lounge are all wireless and all of the classrooms have built-in computer and projection systems.

### Research Areas

- Biofuels and Biocatalysis
- Biomolecular Engineering and Biotechnology
- Catalysis, Combustion, Kinetics and Electrochemical Reaction Engineering
- Computational Nanoscience and Biology
- Electronic Materials
- Environmental Studies/Green Engineering
- Nanoscience and Nanotechnology
- Polymers and Innovative Textiles

### Our Faculty

Peter S. Fedkiw (Dept. Head) • Jan Genzer (Assoc. Dept. Head) • Chase L. Beisel • Joseph M. DeSimone • Ruben G. Carbonell • Michael C. Flickinger • Keith E. Gubbins • Carol K. Hall • Jason M. Haugh • Christine S. Grant • Robert M. Kelly • Richard J. Spontak • Steven W. Peretti • Saad A. Khan • P.K. Lim • David F. Ollis • Gregory N. Parsons • Orlin D. Velez • Bala Rao • Michael Dickey • H. Henry Lamb • Gregory T. Reeves • Wesley A. Henderson • Phillip R. Westmoreland

**Contact:** Dr. Jason M. Haugh, Director of Graduate Recruiting  
Dept. of Chemical & Biomolecular Engineering  
Campus Box 7905, NC State University  
Raleigh, NC 27695-7905  
(email) [cbe@ncsu.edu](mailto:cbe@ncsu.edu)



**McCormick**

**Northwestern Engineering**

## **Chemical and Biological Engineering**

**Luis A. N. Amaral, Ph.D., Boston University, 1996**

*Complex systems, computational physics, biological networks*

**Linda J. Broadbelt, Ph.D., Delaware, 1994**

*Reaction engineering, kinetics modeling, polymer resource recovery*

**Wesley R. Burghardt, Ph.D., Stanford, 1990**

*Polymer science, rheology*

**Stephen H. Davis, Ph.D.,**

**Rensselaer Polytechnic Institute, 1964**

*Theoretical fluid mechanics, material science*

**Kimberly A. Gray, Ph.D., Johns Hopkins, 1988**

*Catalysis, treatment technologies, environmental chemistry*

**Bartosz A. Grzyowski, Ph.D., Harvard, 2000**

*Complex chemical systems*

**Michael C. Jewett, Ph.D., Stanford, 2005**

*Synthetic biology, systems biology, metabolic engineering*

**Harold H. Kung, Ph.D., Northwestern, 1974**

*Kinetics, heterogeneous catalysis*

**Joshua N. Leonard, Ph.D., Berkeley, 2006**

*Cellular & biomolecular engineering for medicine, systems biology*

**Phillip B. Messersmith, Ph.D.,**

**University of Illinois at Urbana-Champaign**

*Biomimetic/Bioinspired materials*

**William M. Miller, Ph.D., Berkeley, 1987**

*Cell culture for biotechnology and medicine*

**Chad Mirkin, Ph.D., Penn State, 1986**

*Inorganic, materials, physical/analytical*

**Justin M. Notestein, Ph.D., Berkeley, 2006**

*Materials design for adsorption and catalysis*

**Monica Olvera de la Cruz, Ph.D., Cambridge, 1984**

*Statistical mechanics in polymer systems*

**Julio M. Ottino, Ph.D., Minnesota, 1979**

*Fluid mechanics, granular materials, chaos, mixing in materials processing*

**Gregory Ryskin, Ph.D., Caltech, 1983**

*Fluid mechanics, computational methods, polymeric liquids*

**George C. Schatz, Ph.D.,**

**California Institute of Technology Research**

*Materials, physical/analytical*

**Lonnie D. Shea, Ph.D., Michigan, 1997**

*Tissue engineering, gene therapy*

**Randall Q. Snurr, Ph.D., Berkeley 1994**

*Adsorption and diffusion in porous media, molecular modeling*

**Igal Szleifer, Ph.D., Hebrew University, 1989**

*Molecular modeling of biointerfaces*

**John M. Torkelson, Ph.D., Minnesota, 1983**

*Polymer science, membranes*

***For information and application to the graduate program, please contact:***

Director of Graduate Admissions  
Department of Chemical and Biological Engineering  
Phone (847) 491-7398 or  
(800) 848-5135 (U.S. only)

[admissions-chem-biol-eng@northwestern.edu](mailto:admissions-chem-biol-eng@northwestern.edu)

**Or visit our website at**  
[www.chem-biol-eng.northwestern.edu](http://www.chem-biol-eng.northwestern.edu)

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## CHEMICAL AND BIOMOLECULAR ENGINEERING

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### 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/integrated 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

**David 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 programming & analysis in health care, Environment & Process operations

**David T. Leighton, Jr., Professor**

Complex fluids, Biochemical separations & flows

**Edward J. Maginn, Professor**

Chemical systems/catalysis, ionic liquids, computation & theory, energy & environment, materials

**Mark J. McCready, Professor & Chair**

Chemical systems, multi-phase flow, fuel cells, energy & environment, microfluidics, 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](mailto:chegdept.1@nd.edu)  
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# The Ohio State University



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**Aravind R. Asthagiri, Carnegie Mellon**

Developing and applying multi-scale modeling methods to predict material properties entirely from first-principles atomistic simulations

**Bhavik R. Bakshi, MIT**

Industrial ecology, process engineering, and analysis of complex systems

**Robert S. Brodkey, Wisconsin**

Experimental measurements for validation of computational fluid mechanics and applications to mixing process applications

**Jeffrey J. Chalmers, Cornell**

Immunomagnetic cell separation, effect of hydrodynamic forces on cells, interfacial phenomena and cells, bioengineering, biotechnology, and cancer detection

**Stuart L. Cooper, Princeton**

Polymer science and engineering, properties of polyurethanes and ionomers, polyurethane biomaterials, blood-material interactions, and tissue engineering

**Liang-Shih Fan, West Virginia**

Fluidization, particle technology, and particulates reaction engineering

**Martin Feinberg, Princeton**

Mathematics of complex chemical systems

**Winston Ho, Illinois-Urbana**

Membrane separations with chemical reaction and fuel-cell fuel Processing

**Kurt W. Koelling, Princeton**

Rheology, polymer processing, and microfluidics

**Isamu Kusaka, CalTech**

Statistical mechanics and nucleation

**L. James Lee, Minnesota**

Polymer and composite processing, micro/nano-fabrication, and bioMEMS

**Umit S. Ozkan, Iowa State**

Heterogeneous catalysis, kinetics, and catalytic materials

**Andre F. Palmer, Johns Hopkins**

Artificial blood substitutes, protein and tissue engineering, drug delivery, and Rheo-optics of complex fluids

**Michael Paulaitis, University of Illinois**

Molecular simulations and modeling of weak protein-protein interactions, the role of hydration in biological organization and self-assembly phenomena, and multiscale modeling of biological interactions

**James F. Rathman, Oklahoma**

Colloids, interfaces, surfactants, molecular self-assembly, and bioinformatics

**David L. Tomasko, Illinois-Urbana**

Separations, molecular thermodynamics, and materials processing in supercritical fluids

**Jessica O. Winter, University Of Texas at Austin**

Nanobiotechnology, cell and tissue engineering, and neural prosthetics

**David Wood, Rensselaer Polytechnic Institute**

Biotechnology development through protein engineering, commodity enzyme production, therapeutic protein development and high-throughput screening

**Barbara E. Wyslouzil, CalTech**

Nucleation, aerosol formation, growth and transport, atmospheric aerosols, thermodynamics, and phase equilibria

**Shang-Tian Yang, Purdue**

Biochemical engineering, biotechnology, and tissue engineering

**Jacques L. Zakin, New York**

Rheology, drag reduction, surfactant microstructures, and heat transfer enhancement

**For complete information please write, call, email or visit us online!**

Graduate Program Coordinator  
Department of Chemical & Biomolecular Engineering  
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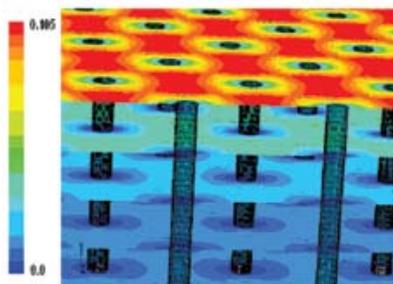
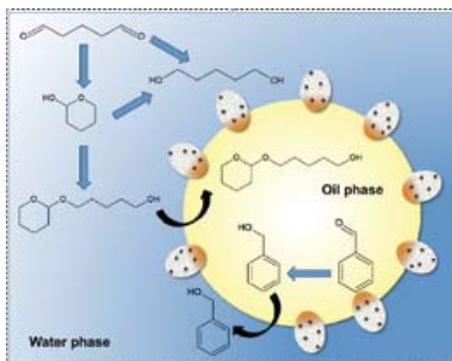
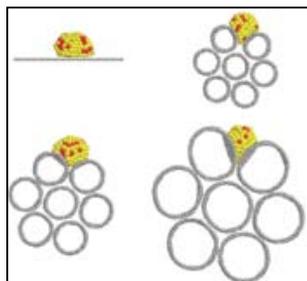
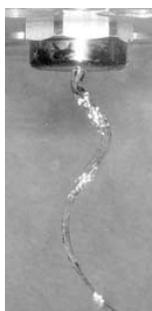
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Research in the School of Chemical, Biological and Materials Engineering (CBME) is characterized by INNOVATION AND IMPACT, leading to patents, technology licenses, companies and sought-after graduates.



## Research Areas

### Bioengineering/Biomedical Engineering

Genetic engineering, protein production, bioseparations, metabolic engineering, biological transport, cancer treatment, cell adhesion, biosensors, orthopedic tissue engineering.

### Energy and Chemicals

Biofuels and catalytic biomass conversion, catalytic hydrocarbon processing, plasma processing, data reconciliation, process design retrofit and optimization, molecular thermodynamics, computational modeling of turbulent transport and reactive flows, detergency, improved oil recovery.

### Materials Science and Engineering

Single wall carbon nanotube production and functionalization, surface characterization, polymer melt blowing, polymer characterization and structure-property relationships, polymer nanolayer formation and use, biomaterials.

### Environmental Processes

Zero-discharge process engineering, soil and aquifer remediation, surfactant-based water decontamination, sustainable energy processes.

For detailed information, visit our Web site at:  
<http://www.ou.edu/coe/cbme.html>

## Faculty Members

**Miguel J. Bagajewicz**  
Ph.D. California Institute of Technology, 1987

**Brian P. Grady**  
Ph.D. University of Wisconsin-Madison, 1994

**Roger G. Harrison, Jr.**  
Ph.D. University of Wisconsin-Madison, 1975

**Jeffrey H. Harwell**  
Ph.D. University of Texas, Austin, 1983

**Dr. Peter J. Heinzelman**  
Ph.D. MIT, 2006

**Friederike C. Jentoff**  
Ph.D. Ludwig-Maximilians-Universität München, Germany, 1994

**Lance L. Lobban**  
Ph.D. University of Houston, 1987

**Richard G. Mallinson**  
Ph.D. Purdue University, 1983

**M. Ulli Nollert**  
Ph.D. Cornell University, 1987

**Edgar A. O'Rear, III**  
Ph.D. Rice University, 1981

**Dimitrios V. Papavassiliou**  
Ph.D. University of Illinois at Urbana-Champaign, 1996

**Daniel E. Resasco**  
Ph.D. Yale University, 1983

**David W. Schmidtke**  
Ph.D. University of Texas, Austin, 1980

**Robert L. Shambaugh**  
Ph.D. Case Western Reserve University, 1976

**Vassilios I. Sikavitsas**  
Ph.D. University of Buffalo, 2000

**Alberto Striolo**  
Ph.D. University of Padova, Italy, 2002

For more information,  
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Chairman,  
Graduate Program Committee,  
School of Chemical, Biological  
and Materials Engineering,  
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T-335 Sarkeys Energy Center,  
100 E. Boyd St.,  
Norman, OK 73019-1004 USA  
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Phone: (405)-325-5811,  
(800) 601-9360,  
Fax:(405) 325-5813

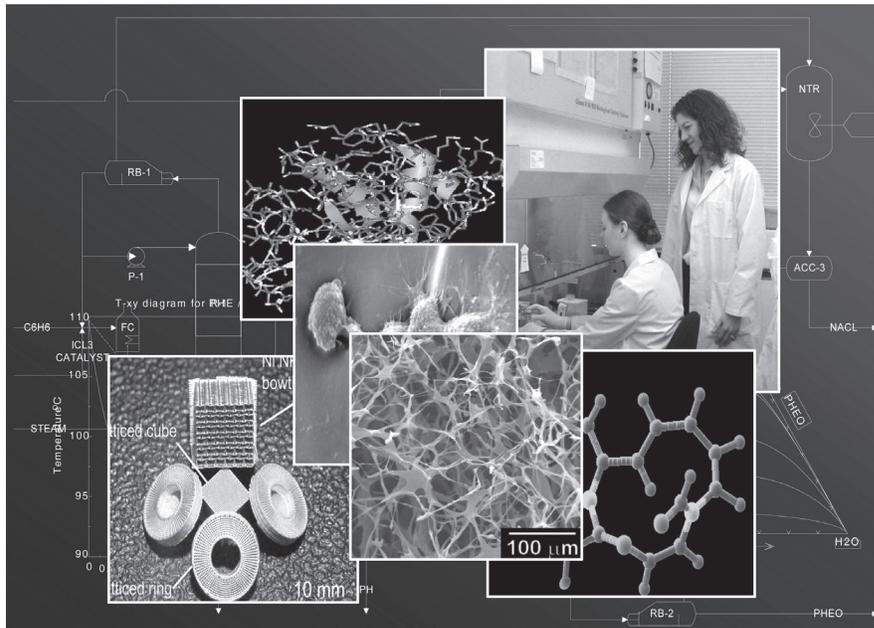


# SCHOOL OF Chemical Engineering

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., UNIVERSITIES 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  
CO<sub>2</sub> SEQUESTRATION

ION EXCHANGE  
MOLECULAR DESIGN  
NANOMATERIALS  
OPTIMIZATION  
PHASE EQUILIBRIA  
POLYMERS  
PROCESS CONTROL

PROCESS SIMULATION  
PRODUCT MODELING  
SOLID FREEFORM FABRICATION  
TISSUE ENGINEERING  
TRANSDERMAL DRUG DELIVERY

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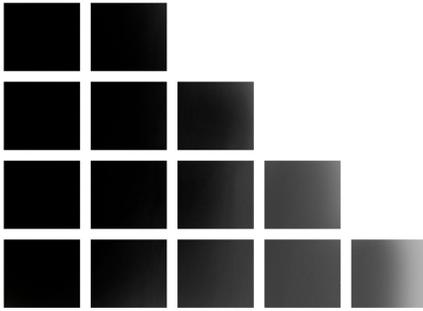
**Dr. Khaled A.M. Gasem**  
School of Chemical Engineering  
Oklahoma State University  
Stillwater, OK 74078-5021  
T 405 744 5280  
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www.cheng.okstate.edu



[cheng.okstate.edu](http://cheng.okstate.edu)



# Chemical and Biological Engineering, **uOttawa**



With a population of close to 1 million, Ottawa offers numerous natural, cultural, and historical attractions year-round and is ranked as one of the most liveable places in the world. Situated at its heart is the University of Ottawa, providing over 220 undergraduate, graduate and professional degree programs in a bilingual, cosmopolitan environment. With its state of the art teaching and research facilities and world class faculty members, the Department of Chemical and Biological Engineering is home to a diverse, enthusiastic and talented family of undergraduate and graduate students.

#### **Our Graduate Programs:**

The Department offers part-time and full-time Master of Applied Science (MASc) and Doctor of Philosophy (PhD) programs, as well as a coursework-based Master of Engineering (MEng) degree.

#### **Financial Aid:**

Financial aid through scholarships, teaching assistantships, and research assistantships is available for qualified applicants. Attractive top-ups are available for those who hold sources of external funding.



Photography and design: David Taylor (david.taylor@uOttawa.ca)

- Elena Baranova *Process Engineering, Renewable Energy*
- Xudong Cao *Tissue Engineering*
- Marc Dubé *Biodiesel, Polymer Reaction Engineering*
- Marianne Fenech *Biofluid Mechanics*
- Kevin Kennedy *Renewable Energy*
- Kathlyn Kirkwood *Bioengineering, Renewable Energy*
- Boguslaw Kruczek *Process Engineering, Renewable Energy*
- Christopher Lan *Biofuels, Bioprocessing, Membrane Technologies*
- Arturo Macchi *Multiphase Reaction Engineering*
- Poupak Mehrani *Process Engineering*
- Sidney Omelon *Crystallization, Biomedical Engineering*
- David Taylor *Process Modelling and Simulation*
- Handan Tezel *Process Engineering, Renewable Energy*
- Jules Thibault *Bioengineering, Process Engineering*
- André Tremblay *Biodiesel, Synthetic Membranes, Process Integration*
- Jason Zhang *Bioengineering, Renewable Energy*

**Considering Graduate Studies in Chemical Engineering? Consider uOttawa:**  
**[www.engineering.uottawa.ca/chemicalengineering](http://www.engineering.uottawa.ca/chemicalengineering)**

# University of Pennsylvania

## Chemical and Biomolecular Engineering

**Tobias Baumgart** *Physical chemistry and mechanics of biological membranes, cell/surface interactions*

**Russell J. Composto** *Polymeric materials science, surface and interface studies*

**Christopher S. Chen** *Stem cell differentiation, angiogenesis, engineering extracellular matrix, cell cell adhesion, mechanotransduction, multicellularity*

**John C. Crocker** *Single-molecule biophysics, cell mechanics, soft glasses*

**Scott L. Diamond** *Protein and gene delivery, mechano-biology, blood systems biology, drug discovery*

**Dennis E. Discher** *Polymersomes, protein folding, stem cell rheology, gene and drug delivery*

**Eduardo D. Glandt** *Classical and statistical thermodynamics, random media*

**Raymond J. Gorte** *Heterogeneous catalysis, supported metals, oxide catalysis, electrodes for solid-oxide fuel cells*

**Daniel A. Hammer** *Cellular bioengineering, biointerfacial phenomena, adhesion*

**Matthew J. Lazzara** *Cellular engineering, cell signaling, molecular therapeutics*

**Daeyeon Lee** *Surface and interface science; polymer/nanoparticle thin films; microfluidics; emulsion science; stimuli-responsive microcapsules*

**Ravi Radhakrishnan** *Statistical mechanics, quantum chemistry, biomolecular and cellular signaling*

**Robert A. Riggleman** *Molecular modeling, statistical mechanics, and polymer glasses*

**Casim A. Sarkar** *Biomolecular engineering, cellular engineering, biotechnology*

**Warren D. Seider** *Process analysis, simulation, design, and control*

**Wen K. Shieh** *Bioenvironmental engineering, environmental systems modeling*

**Talid R. Sinno** *Transport and reaction, statistical mechanical modeling*

**Kathleen J. Stebe** *Nanomaterials, surfaces and interfaces, dynamics of self assembly, surfactants*

**John M. Vohs** *Surface science, catalysis, electronic materials processing*

**Karen I. Winey** *Polymer morphology, processing, and property interrelationships*

**Shu Yang** *Synthesis, characterization and fabrication of functional polymers, and organic/inorganic hybrids*

**Penn's graduate program in chemical and biomolecular engineering provides flexibility while emphasizing the fundamental nature of chemical and physical processes. Students may focus their studies in any of the research areas of the department. The full resources of this Ivy League university, including the Wharton School of Business and one of the country's foremost medical centers, are available to students in the program. The cultural advantages, historical assets, and recreational facilities of a great city are within walking distance of the university.**



*For additional information, write:*

Director of Graduate Admissions  
Chemical and Biomolecular Engineering  
University of Pennsylvania  
220 South 33rd Street, Rm. 311A  
Philadelphia, PA 19104-6393

[chegrad@seas.upenn.edu](mailto:chegrad@seas.upenn.edu)

<http://www.seas.upenn.edu/cbe/>



# Chemical Engineering

**PENN STATE'S** Chemical Engineering graduate degree program is located on a diverse, Big-Ten university campus in a vibrant college community. When you join our program, you'll use state-of-the-art facilities such as the Materials Research Institute, the Huck Institutes of the Life Sciences, and one of the foremost nanofabrication facilities in the world. We provide fellowships and research assistantships, including tuition and fees.

Research at Penn State spans the spectrum of chemical engineering with focus areas in biomolecular engineering, alternative energy, and nanotechnology.

## FACULTY

### ANTONIOS ARMAOU

PH.D., UCLA—Process control and system dynamics

### KYLE BISHOP

PH.D., NORTHWESTERN—Complex dissipative systems: flame plasmas, chemical reaction networks, reaction-diffusion systems

### ALI BORHAN

PH.D., STANFORD—Fluid dynamics, transport phenomena, capillary and interfacial phenomena

### WAYNE CURTIS

PH.D., PURDUE—Plant cell tissue culture, secondary metabolism, bioreactor design

### RONALD DANNER

PH.D., LEHIGH—Phase equilibria and diffusion in polymer-solvent and gas solid systems

### KRISTEN FICHTHORN

PH.D., UNIVERSITY OF MICHIGAN  
Atomistic simulation, statistical mechanics, surface science, materials

### HENRY FOLEY

PH.D., PENN STATE—Nanomaterials, reaction and separation, catalysis

### ENRIQUE GOMEZ

PH.D., BERKELEY—Organic photovoltaics, organic-inorganic interfaces, nanostructured polymers

### ESTHER GOMEZ

PH.D., BERKELEY—Bioengineering, cell and tissue mechanics, biosensors

### MICHAEL JANIK

PH.D., UNIVERSITY OF VIRGINIA  
Fuel cells and electrochemical systems for renewable energy sources

### SEONG KIM

PH.D., NORTHWESTERN—Surface science, polymers, thin films, nanotribology, nanomaterials

### MANISH KUMAR

PH.D., UNIVERSITY OF ILLINOIS—Biomimetic membranes, membrane proteins, membrane technology, desalination

### COSTAS MARANAS

PH.D., PRINCETON—Computational protein design; reconstruction, curation, and analysis of metabolic networks; microbial strain optimization; design of biological circuits and synthetic biology; signaling networks and multiscale modeling in cancer biology, network science, optimization theory, and algorithms

### JANNA MARANAS

PH.D., PRINCETON—Nano-scale structure and mobility in soft materials, with applications in alternative energy, biology, and polymer physics

### THEMIS MATSOUKAS

PH.D., UNIVERSITY OF MICHIGAN  
Aerosol engineering, colloids, plasma processing

### SCOTT MILNER

PH.D., HARVARD—Glass transitions in dense fluids and polymer films, flow behavior of entangled polymers, polymer crystallization

### JOSEPH PEREZ

PH.D., PENN STATE—Tribology, lubrication, biodiesel

### ROBERT RIOUX

PH.D., BERKELEY—Heterogeneous catalysis, nanostructure synthesis, renewable energy, atomic-level characterization, single molecule chemistry

### HOWARD SALIS

PH.D., UNIVERSITY OF MINNESOTA—Synthetic biology, metabolic engineering, design of genetic systems

### DARRELL VELEGOL

PH.D., CARNEGIE MELLON  
Colloidal and nanocolloidal devices and systems

### JAMES VRENTAS

PH.D., UNIVERSITY OF DELAWARE  
Transport phenomena, applied mathematics, fluid mechanics, diffusion, polymer science

### ANDREW ZYDNEY

PH.D., MIT—Development of membrane systems for bioprocessing applications, mass transfer characteristics of artificial organ systems

## FOR MORE INFORMATION

Janna Maranas, Graduate Admissions Chair  
158 Fenske Laboratory  
Department of Chemical Engineering  
The Pennsylvania State University  
University Park, PA 16802

814-863-6228 [jmaranas@enr.psu.edu](mailto:jmaranas@enr.psu.edu)

PENNSTATE



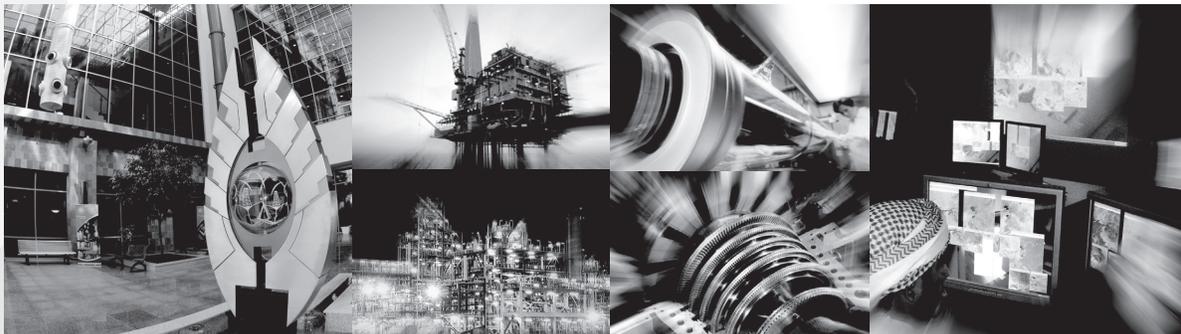
[fenske.che.psu.edu](http://fenske.che.psu.edu)

*Chemical Engineering Education*



# المعهد البترولي

THE PETROLEUM INSTITUTE ABU DHABI



**The Petroleum Institute (PI)** is devoted to engineering education and research in areas of importance to the energy sector. PI's sponsors and affiliates include the Abu Dhabi National Oil Company (ADNOC), BP, Shell, Jodco, and Total. The Institute has modern laboratories and facilities with the creation of additional research centers underway. PI is affiliated with and has collaborative education and research programs with major research Universities in the USA, Europe and China.

We are inviting applications for admission to the graduate program in chemical engineering in Spring 2011 or Fall 2011. If you are a recent graduate motivated to undertake a challenging and rigorous program of study and research in all areas of chemical engineering and would like to pursue a Master of Engineering degree, a Master of Science degree, or a PhD degree in collaboration with one of our partner Universities, you are encouraged to apply for admission.

The current Graduate Program Catalogue is available at the following URL:

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**[http://www.pi.ac.ae/PI\\_ACA/pgp/fellow\\_who.php](http://www.pi.ac.ae/PI_ACA/pgp/fellow_who.php)**

**Application Deadlines:**

Fall Semester: 1 April - Spring Semester: 1 October

## Faculty

### J.R. Kim

Protein engineering, folding, aggregation and stability

### R. Levicky

Biosensors, nanobiotechnology

### J. Mijovic

Relaxation dynamics in synthetic and biological macromolecules

### S. Sofou

Heterogeneous lipid membranes, drug delivery

### L. Stiel

Thermodynamics and transport properties of fluids

### E. Ziegler

Air pollution control engineering

### W. Zurawsky

Plasma polymerization, polymer thin films

A number of fellowships are available in our MS and PhD Chemical Engineering programs.

For more information, contact:

### Professor Walter Zurawsky

Head, Department of Chemical and Biological Engineering  
Six MetroTech Center  
Brooklyn, NY 11201

718.260.3725

[www.poly.edu/cbe](http://www.poly.edu/cbe)

## Innovation begins at NYU-Poly: DEVisING THE FUTURE OF BIODETECTION DEVICES

**NYU-Poly Professor Rastislav Levicky** is designing advanced technologies for applications in healthcare, drug development and pathogen detection. Working largely with biosensors made from synthetic DNA mimics, Levicky uses electrochemical detection techniques to improve the performance and economic accessibility of point-of-care medical diagnostics. This kind of thinking comes from the NYU-Poly culture of invention, innovation and entrepreneurship. We call it *i<sup>2</sup>e*. NYU-Poly and our *i<sup>2</sup>e* philosophy transform our faculty and students by arming them with the tools, resources and inspiration they need to turn their research into revolutionary applications, products and services.



NEW YORK UNIVERSITY

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and entrepreneurship



# Princeton University

## *Ph.D. and M.Eng. Programs in Chemical and Biological Engineering*



### **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)

#### **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*



**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

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## Faculty

Rakesh Agrawal  
Chelsey D. Baertsch  
Osman A. Basaran  
Stephen P. Beaudoin  
James M. Caruthers  
Raj Chakrabarti  
David S. Corti  
W. Nicholas Delgass  
Elias I. Franses  
Robert E. Hannemann  
Michael T. Harris  
Hugh W. Hillhouse  
R. Neal Houze  
Sangtae Kim  
James D. Litster  
Julie Liu  
John A. Morgan  
Joseph F. Pekny  
R. Byron Pipes  
D. Ramkrishna  
G. V. Reklaitis  
Fabio H. Ribeiro  
Kendall T. Thomson  
Arvind Varma (Head)  
V. Venkatasubramanian  
Nien-Hwa L. Wang  
Phillip C. Wankat  
You-Yeon Won  
Yue Wu  
Chongli Yuan

## Preeminence in Discovery, Learning, and Engagement

### Research areas

- Biochemical Engineering • Biomaterials • Biomolecular Engineering
- Catalysis & Reaction Engineering • Clean & Renewable Energy
- Combustion Synthesis • Electronic Materials
- Fluid Mechanics & Transport Phenomena
- Interfacial Engineering & Colloid Science • Micro & Nanofluidics
- Molecular Modeling & Statistical Mechanics • Nanofabrication & Nanomaterials
- Pharmaceutical Engineering • Polymer Materials & Composites
- Product & Process Systems Engineering • Separation Processes • Surface Science

The School of Chemical Engineering (ChE), the College of Engineering (COE), and Purdue University have been undergoing exciting transformations befitting the dawn of a new century. These changes range from the creation of 95 and 300 entirely new faculty positions in the COE and the university, respectively, and the completion of Discovery Park, a new \$350 million multidisciplinary home for research in signature areas of importance to society. In ChE, thirteen new faculty, a mix of freshly minted PhDs, senior academics, and renowned researchers, have joined our ranks since 2003. The current ChE faculty includes five members of the National Academy of Engineering. To house the expanded faculty, students, and research and teaching activities, a new building, the Forney Hall of Chemical Engineering, was completed in 2005 and the original one is undergoing full renovation.

For more information, contact:

Graduate Studies, Forney Hall of Chemical Engineering,  
Purdue University  
480 Stadium Mall Drive  
West Lafayette, IN 47907  
Phone: (765) 494-4057  
Web: <http://engineering.purdue.edu/ChE>



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](mailto:admissions@rpi.edu)  
<http://admissions.rpi.edu/graduate/>

## *Faculty and Research Interests*

**Georges Belfort**, [belfog@rpi.edu](mailto:belfog@rpi.edu)

Membrane separations; adsorption; biocatalysis; MRI; interfacial phenomena

**B. Wayne Bequette**, [bequette@rpi.edu](mailto:bequette@rpi.edu)

Process control; fuel cell systems; biomedical systems

**Cynthia H. Collins**, [ccollins@rpi.edu](mailto:ccollins@rpi.edu)

Systems biology; protein engineering; intercellular communication systems; synthetic microbial ecosystems

**Marc-Olivier Coppens**, [coppens@rpi.edu](mailto:coppens@rpi.edu)

Nature-inspired chemical engineering; mathematical & computational modeling; statistical mechanics; nanoporous materials synthesis; reaction engineering

**Steven M. Cramer**, [cramess@rpi.edu](mailto:cramess@rpi.edu)

Displacement, membrane and preparative chromatography; environmental research

**Jonathan S. Dordick**, [dordick@rpi.edu](mailto:dordick@rpi.edu)

Biochemical engineering; biocatalysis; polymer science; bioseparations

**Shekhar Garde**, [gardes@rpi.edu](mailto:gardes@rpi.edu), *Department Head*

Macromolecular self-assembly, computer simulations, statistical thermodynamics of liquids, hydration phenomena

**Ravi Kane**, [kaner@rpi.edu](mailto:kaner@rpi.edu)

Polymers; biosurfaces; biomaterials; nanomaterials, nanobiotechnology

**Pankaj Karande**, [karanp@rpi.edu](mailto:karanp@rpi.edu)

Drug delivery; combinatorial chemistry; molecular modeling; high throughput screening

**Lealon L. Martin**, [lealon@rpi.edu](mailto:lealon@rpi.edu)

Chemical and biological process modeling and design; optimization; systems engineering

**Joel L. Plawsky**, [plawsky@rpi.edu](mailto:plawsky@rpi.edu)

Electronic and photonic materials; interfacial phenomena; transport phenomena

**Peter M. Tessier**, [tessier@rpi.edu](mailto:tessier@rpi.edu)

Protein-protein interactions, protein self-assembly and aggregation

**Patrick T. Underhill**, [underhill@rpi.edu](mailto:underhill@rpi.edu)

Transport phenomena, multi-scale model development and applications to colloidal, polymer, and biological systems

---

## *Emeritus Faculty*

**Elmar R. Altwick**, [altwie@rpi.edu](mailto:altwie@rpi.edu)

Spouted-bed combustion; incineration; trace pollutant kinetics

**Henry R. Bungay III**, [bungah@rpi.edu](mailto:bungah@rpi.edu)

Wastewater treatment; biochemical engineering

**Arthur Fontijn**, [fontia@rpi.edu](mailto:fontia@rpi.edu)

Combustion; high temperature kinetics; gas-phase reactions

**William N. Gill**, [gilln@rpi.edu](mailto:gilln@rpi.edu)

Microelectronics; reverse osmosis; crystal growth; ceramic composites

**Howard Littman**, [littmh@rpi.edu](mailto:littmh@rpi.edu)

Fluid/particle systems; fluidization; spouting bed; pneumatic transport

**Peter C. Wayner, Jr.**, [wayner@rpi.edu](mailto:wayner@rpi.edu)

Heat transfer; interfacial phenomena; porous materials



# 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 Zygorakis**  
(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)



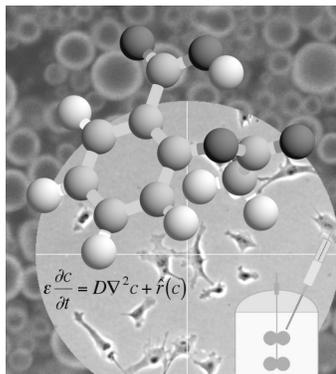
## CHEMICAL AND BIOMOLECULAR ENGINEERING @ RICE

### 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<sub>2</sub> 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

### *Clean Energy*

- Fuel Cells
- Solar Cells
- Biofuels
- Green Engineering

### *Nanotechnology*

- Thin Film Devices
- Photonics & Optoelectronics
- Nanofabrication
- Display Technologies

### *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**

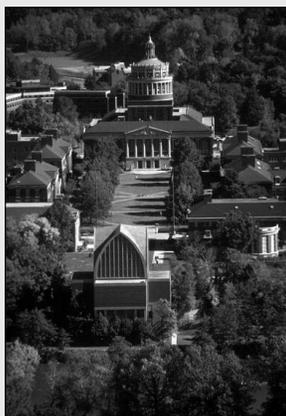
Ph.D., MIT, 1987  
bone marrow tissue engineering, stem cell and lymphocyte cultures, enzymology of biomass energy process

### **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](mailto:chegradinfo@che.rochester.edu)



**HAJIM**  
SCHOOL OF ENGINEERING  
& APPLIED SCIENCES  
UNIVERSITY OF ROCHESTER





**HAJIM**  
SCHOOL OF ENGINEERING  
& APPLIED SCIENCES  
UNIVERSITY of ROCHESTER

## Master's of Science

### Alternative Energy

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



<http://www.che.rochester.edu/altenergy.htm>



### 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

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## *Master of Science*

---

## *Chemical Engineering*



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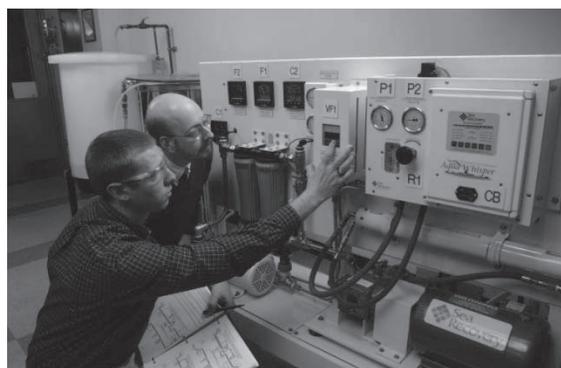
The Chemical Engineering Department at Rowan University is housed in Henry M. Rowan Hall, a state-of-the-art, 95,000 sq. ft. multidisciplinary teaching and research space. An emphasis on project management and industrially relevant research prepares students for successful careers in high-tech fields. The new South Jersey Technology Center will provide further opportunities for student training in emerging technologies.

Located in southern New Jersey, the nearby orchards and farms are a daily reminder that this is the Garden State. Cultural and recreational opportunities are plentiful in the area. Philadelphia and the scenic Jersey Shore are only a short drive, and major metropolitan areas are within easy reach.

### *Faculty*

---

**Robert P. Hesketh**, Chair • *University of Delaware*  
**Kevin Dahm** • *Massachusetts Institute of Technology*  
**Stephanie Farrell** • *New Jersey Institute of Technology*  
**Zenaida Gephardt** • *University of Delaware*  
**Mariano J. Savelski** • *University of Oklahoma*  
**C. Stewart Slater** • *Rutgers University*  
**Jennifer Vernengo** • *Drexel University*  
**Mary Staehle** • *University of Delaware*



### *Research Areas*

Membrane Separations • Pharmaceutical and Food Processing Technology • Biochemical Engineering • Systems Biology • Biomaterials • Green Engineering • Controlled Release • Kinetic and Mechanistic Modeling of Complex Reaction Systems • Reaction Engineering • Novel Separation Processes • Process Design and Optimization • Particle Technology • Renewable Fuels • Lean Manufacturing Sustainable Design

### *For additional information*

---

Dr. Mary Staehle • Graduate Program Coordinator • Department of Chemical Engineering •  
Rowan University • 201 Mullica Hill Road • Glassboro, NJ 08028

Phone: (856) 256-5310 • Fax: (856) 256-5242

E-mail: [staehle@rowan.edu](mailto:staehle@rowan.edu) • Web: <http://www.rowan.edu/open/colleges/engineering/>



# Research is part of the program

*Located 150 km east of Montreal, Sherbrooke is a university town of 150,000 inhabitants offering all the advantages of city life in a rural environment.*

*With strong ties to industry, the Department of Chemical and Biotechnological Engineering offers graduate programs leading to a master's degree (thesis and non-thesis) and a PhD degree.*

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819-821-7171  
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 UNIVERSITÉ DE  
SHERBROOKE

**Nicolas ABATZOGLOU**  
*Department Chair, Wyeth/UdeS Industrial Chair on PAT. Particulate systems, multiphase catalytic reactors, pharmaceutical engineering*

**Nadi BRAIDY**  
*Material engineering, nanosciences and nanotechnologies, materials characterization*

**Nathalie FAUCHEUX**  
*Canada Research Chair Cell-biomaterial biohybrid system, cancer and biomaterials, bone repair and substitute*

**François GITZHOFER**  
*Thermal plasma materials synthesis, plasma spraying, materials characterization, SOFC*

**Ryan GOSSELIN**  
*Pharmaceutical engineering (PAT), industrial process control, spectral imagery*

**Michèle HEITZ**  
*Air treatment, biofiltration, bioenergy, biodiesel, biovalorization of agro-food wastes*

**Michel HUNEALT**  
*Polymer alloys, melt state biopolymer processing, materials characterization*

**J. Peter JONES**  
*Treatment of industrial wastewater, design of experiments, treatment of endocrine disruptors*

**Jerzy JUREWICZ**  
*Nanometric powder synthesis, extractive metallurgy, DC and HF plasma generation*

**Jean-Michel LAVOIE**, *Cellulosic Ethanol Industrial Chair,*  
*Biofuels industrial organic synthesis*

**Bernard MARCOS**  
*Chemical and biotechnological processes modeling, energy systems modeling*

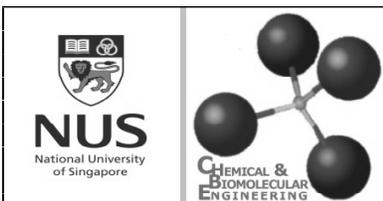
**Joisane NIKIEMA**  
*Industrial wastewater treatment, biological processes optimization*

**Pierre PROULX**  
*Modeling and numerical simulation, optimization of reactors, transport phenomena*

**Joël SIROIS**  
*Suspension and cell metabolism, optimization of biosystems, bioactive principles production*

**Gervais SOUCY**  
*Aluminum and thermal plasma technology, carbon nanostructures, materials characterization*

**Patrick VERMETTE**  
*Tissue engineering and biomaterials, colloids and surface chemistry, drug delivery systems*



## Department of *Chemical and Biomolecular Engineering*

As part of a distinguished University that is ranked 3<sup>rd</sup> in Asia (*Quacquarelli Symonds Asian University Rankings 2010*) and 30<sup>th</sup> in the world (*Quacquarelli Symonds World University Rankings 2009*), we offer a comprehensive selection of courses and activities for a distinctive and enriching learning experience. You will benefit from the opportunity to work with our diverse faculty in a cosmopolitan environment. **Join us at NUS – Singapore’s Global University, and be a part of the future today !**

### Program Features

- Research activities in a broad spectrum of fundamental, applied and emerging technological areas
- Active research collaboration with the industry, national research centers and institutes
- Top-notch facilities for cutting-edge research
- Strong international research collaboration with universities in America, Europe and Asia
- Over 200 research scholars (80% pursuing Ph.D.) from countries such as USA, Germany, Japan, China, India, Vietnam and other countries in the region.
- Joint graduate programs with UIUC, MIT and IIT-Bombay, IIT-Madras
- An array of financial assistance, scholarships and awards available

### Strategic Research & Educational Thrusts

- Biomolecular and Biomedical Engineering
- Chemical Engineering Sciences
- Chemical and Biological Systems
- Energy and Environmentally Sustainable Processes
- Nanostructured Materials & Devices

### Our Graduate Programs

#### Research-based

- Ph.D. and M.Eng.
- NUS-UIUC Joint Ph.D.
- Singapore-MIT Alliance Dual M.Sc. (MIT, NUS) & Ph.D.

#### Coursework-based

- M.Sc. (Chemical Engineering)
- M.Sc. (Safety, Health & Environmental Technology)



**Engineer Your Own Evolution! Reach us at :**  
**National University of Singapore**

Department of Chemical & Biomolecular Engineering  
4 Engineering Drive 4, Singapore 117576

Email: [chbe\\_grad\\_programs@nus.edu.sg](mailto:chbe_grad_programs@nus.edu.sg) • <http://www.chbe.nus.edu.sg> • Fax: +65 6779-1936



# UNIVERSITY OF SOUTH CAROLINA

® COLLEGE OF ENGINEERING AND COMPUTING

The **Department of Chemical Engineering** at USC has emerged as one of the top teaching and research programs in the Southeast. Our program ranks in the top 20 nationally in research expenditures (>\$6 million per year) and annual doctoral graduates. The

Department offers **ME, MS, and PhD** degree programs in **chemical engineering** and **biomedical engineering**.

PhD candidates receive tuition and fee waivers, a health insurance subsidy, and highly competitive stipends starting at **\$25,000 per year**.



The University of South Carolina is located in Columbia, the state capital, which offers the benefits of a big city with the charm and hospitality of a small town. Charlotte and Atlanta, cities that serve as Columbia's international gateways, are nearby. The area's sunny and mild climate, combined with its lakes and wooded parks, provide plenty of opportunities for year-round outdoor recreation.

In addition, Columbia is only hours away from the Blue Ridge Mountains and the Atlantic Coast.

Carolina's mascot, Cocky, shows off on one of our department's hydrogen fuel cell Segways at university events.

## FACULTY

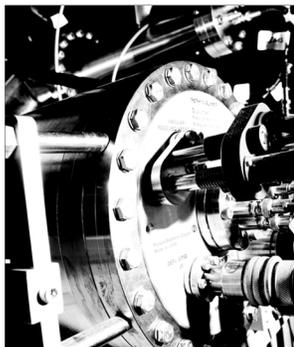
- M.D. Amiridis**, *Wisconsin*  
Provost, Catalysis and Kinetics
- J.O. Blanchette**, *Texas*  
Biomedical Engineering, drug delivery
- C.W. Curtis**, *Florida State*  
Vice provost for faculty development
- F.A. Gadala-Maria**, *Stanford*  
Rheology of suspensions
- E.P. Gatzke**, *Delaware*  
Modeling Control, Optimization
- A. Heyden**, *Hamburg*  
Computational Nanoscience, Catalysis
- E. Jabbari**, *Purdue*  
Biomedical and Tissue Engineering
- E. Jabbarzadeh**, *Drexel*  
Vascular and Cellular Engineering
- J.A. Lauterbach**, *Berlin*  
Environmental Catalysis
- M.A. Matthews**, *Texas A&M*  
Applied Thermodynamics, Supercritical Fluids
- M.A. Moss**, *Kentucky*  
Protein Biophysics, Alzheimer's Disease
- H.J. Ploehn**, *Princeton*  
Interfacial Phenomena, Nanotechnology
- B.N. Popov**, *Illinois*  
Electrochemical Power Sources
- J.A. Ritter**, *SUNY Buffalo*  
Separation and Energy Storage Processes
- T.G. Stanford**, *Michigan*  
Chemical Process Systems
- J.W. Van Zee**, *Texas A&M*  
Electrochemical Engineering, Fuel Cells
- J.W. Weidner**, *NC State*  
Electrochemical Engineering, Electrocatalysis
- R.E. White**, *Cal-Berkeley*  
Electrochemical Engineering, Modelling
- C.T. Williams**, *Purdue*  
Catalysis, Surface Spectroscopy
- X.D. Zhou**, *Missouri Rolla*  
Solid-State Ionics, Elctroics

Contact us: The Graduate Coordinator, Department of Chemical Engineering, Swearingen Engineering Center, University of South Carolina, Columbia, SC 29208. Phone: 800.753.0527 or 803.777.1261. Fax: 803.777.0973. E-mail: chegrad@cec.sc.edu.

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# Department of Chemical & Biomedical Engineering



## 4<sup>th</sup> Largest Producer

Masters of Science Degrees In the United States  
*Chemical & Engineering News* (November 2009)

Our department awarded nine Doctorals, 27 Masters and 29 Bachelor degrees in 2009. The department has 60 PhD students, 65 Master's and 140 undergraduate students currently enrolled. With a **213%** increase between 2000 and 2007, no other American university grew its federal research enterprise at a faster rate than the University of South Florida, according to the Chronicle of Higher Education. USF is ranked **Number 3** in research expenditures in the Big East Conference.

USF is one of only three Florida public universities that are classified by the Carnegie Foundation for the Advancement of Teaching in the top tier of research universities (RU/VH), a distinction attained by only 2.2 percent of all universities. USF is also one of only 25 public research universities nationwide that holds both the RU/VH and the Engaged designations by the Carnegie Foundation.

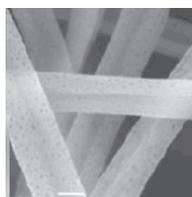
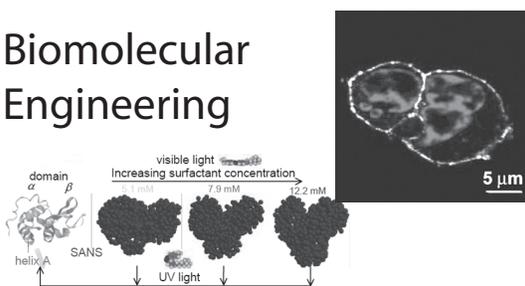
- Advanced Materials
- Biofluidics
- Biomechanics
- Clean Energy & Systems
- Corrosion of Engineering Materials
- Drug & Gene Delivery
- Electrochemistry
- Environmental Engineering
- Fuel Cells
- Hydrogen Production & Storage
- Modeling, Simulation & Control
- Nanotechnology
- Process & Product Design
- Chemical & Biological Sensors
- Smart Materials
- Supercritical Fluids
- Surface Science & Technology
- Sustainability & Green Engineering
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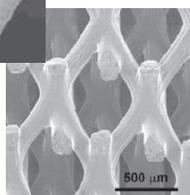
## PhD Programs in Chemical Engineering, Petroleum Engineering, and Materials Science

### Active Research Areas:

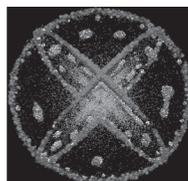
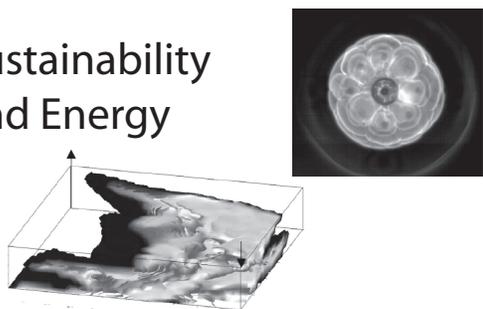
#### Biomolecular Engineering



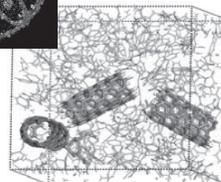
#### Composites and Biomaterials



#### Sustainability and Energy

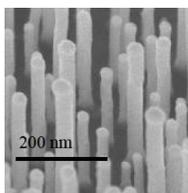


#### Advanced Computation

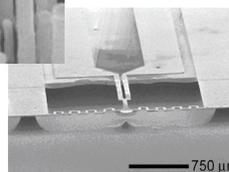


### Academic and Research Highlights:

- ◆ 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.



#### Nanotechnology

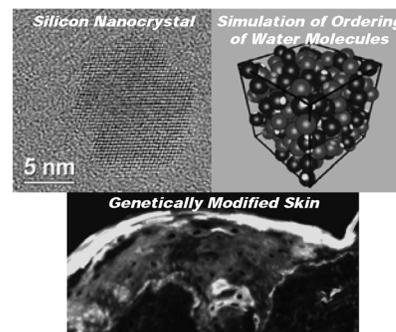
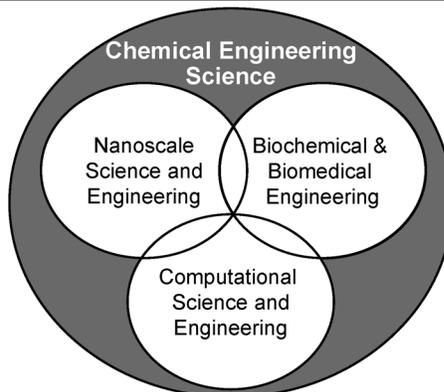


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<http://chems.usc.edu>

**USC Viterbi**  
School of Engineering

## 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 unfolding, 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](mailto: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.



# STEVENS

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## INSTITUTE OF TECHNOLOGY

- Multidisciplinary environment, consisting of chemical and polymer engineering, chemistry, and biology
- Site of two major engineering research centers; Highly Filled Materials Institute; Center for Microchemical Systems
- Scenic campus overlooking the Hudson River and metropolitan New York City
- Close to the world's center of science and culture
- At the hub of major highways, air, rail, and bus lines
- At the center of the country's largest concentration of research laboratories and chemical, petroleum, pharmaceutical, and biotechnology companies

### **Faculty**

---

- P. Akcora** (PhD, University of Maryland, College Park)  
**R. Besser** (PhD, Stanford University)  
**H. Du** (PhD, Penn State University)  
**B. Gallois** (PhD, Carnegie-Mellon University)  
**D.M. Kalyon** (PhD, McGill University)  
**S. Kovenklioglu** (PhD, Stevens Institute of Technology)  
**A. Lawal** (PhD, McGill University)  
**W.Y. Lee** (PhD, Georgia Institute of Technology)  
**M. Libera** (ScD, Massachusetts Inst. of Technology)  
**S. Podkolzin** (PhD, University of Wisconsin–Madison)  
**K. Sheppard** (PhD, University of Birmingham)  
**Y. Zhao** (PhD, Stevens Institute of Technology)

### **Research in**

---

Micro-Chemical Systems  
 Polymer Rheology, Processing, and Characterization  
 Processing of Electronic and Photonic Materials  
 Processing of Highly Filled Materials  
 Chemical Reaction Engineering  
 Biomaterials and Thin Films  
 Polymer Characterization and Morphology  
 High Temperature Gas-Solid and Solid-Solid Interactions  
 Environmental and Thermal Barrier Coatings  
 Biomaterials Design and Synthesis  
 Nanobiotechnology  
 Catalysis at Nanoscale and Reaction Kinetics  
 Nanoparticle Self-Assembly, Self-Healing Polymers and Drug Delivery

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- PH.D.

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 Hoboken, NJ 07030  
 201-216-5319

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 Chemical Engineering and Materials Science Department  
 Stevens Institute of Technology  
 Hoboken, NJ 07030  
 201-216-5546

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Stevens Institute of Technology does not discriminate against any person because of race, creed, color, national origin, sex, age, marital status, handicap, liability for service in the armed forces or status as a disabled or Vietnam era veteran.

# University of Tennessee

## THE FUTURE IS NOW

LIGHTING THE PATH TO TOMORROW'S TECHNOLOGY...TODAY



### 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

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.



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 activities 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](mailto:cheinfo@utk.edu)

<http://www.engr.utk.edu/cbe/>

THE UNIVERSITY of TENNESSEE   
KNOXVILLE

# TTU Tennessee Tech University

**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  
Cementitious 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](mailto: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>

# The University of Texas

## at Austin



*Chemical Engineering* graduate studies at the University of Texas at Austin are exciting, broad-based and interdisciplinary with faculty pursuing diverse research areas. We are one of the leading programs in chemical engineering excelling in all aspects of scholarship, research and education. Both M.S. and Ph.D. ChE degrees are offered. Fellowships and research assistantships, including stipends, tuition and fees, and medical insurance, are provided to qualified applicants.

### *Our Faculty*

**David T. Allen**, Ph.D., Caltech, 1983

**Hal S. Alper**, Ph.D., M.I.T., 2006

**Roger T. Bonnecaze**, Ph.D., Caltech, 1991

**Lydia M. Contreras**, Ph.D., Cornell U., 2008

**James R. Chelikowsky**, Ph.D., U of C. Berkeley, 1975

**Thomas F. Edgar**, Ph.D., Princeton U., 1971

**John G. Ekerdt**, Ph.D., U. of C. Berkeley, 1979

**R. Bruce Eldridge**, Ph.D., U. of Texas, 1986

**Christopher J. Ellison**, Ph.D., Northwestern U., 2005

**Benny D. Freeman**, Ph.D., U. of C. Berkeley, 1988

**Venkat Ganesan**, Ph.D., M.I.T., 1999

**George Georgiou**, Ph.D., Cornell U., 1987

**Adam Heller**, Ph.D., Hebrew U., 1961

**Gyeong S. Hwang**, Ph.D., Caltech, 1999

**Keith P. Johnston**, Ph.D., U. of Illinois, 1981

**Brian A. Korgel**, Ph.D., U. of C. Los Angeles, 1997

**Douglas R. Lloyd**, Ph.D., U. of Waterloo, 1977

**Jennifer Maynard**, Ph.D., U. of Texas, 2002

**Ram Manthiram**, Ph.D., Indian Inst. of Tech., 1980

**C. Buddie Mullins**, Ph.D., Caltech, 1990

**Donald R. Paul**, Ph.D., U. of Wisconsin, 1965

**Nicholas A. Peppas**, Sc.D., M.I.T., 1973

**Danny Reible**, Ph.D., Caltech, 1982

**Gary T. Rochelle**, Ph.D., U. of C. Berkeley, 1977

**Peter J. Rossky**, Ph.D., Harvard U., 1978

**Isaac C. Sanchez**, Ph.D., U. of Delaware, 1969

**Christine E. Schmidt**, Ph.D., U. of Illinois, 1995

**Mukul M. Sharma**, Ph.D., U. of S. California, 1985

**Thomas M. Truskett**, Ph.D., Princeton U., 2001

**C. Grant Willson**, Ph.D., U. of C. Berkeley, 1973

### Areas of study include:

Biomedical and biochemical engineering

Energy resources and sustainability

Nanomaterials

Surface phenomena and catalysis

Polymers and polymer processing

Meso- and molecular scale modeling and simulation

Materials and processes for microelectronics

Systems engineering, process control and optimization

Air and water quality management

Address Inquiries to: Graduate Advisor • Department of Chemical Engineering • The University of Texas  
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## RESEARCH AREAS

*Biomedical and Biomolecular, Complex Fluids, Environmental, Materials, Microelectronics, Microfluidics, Nanotechnology, Process Safety, Process Systems Engineering, Reaction Engineering, Thermodynamics*

## For More Information

Graduate Admissions Office  
 Artie McFerrin Department of Chemical Engineering  
 Dwight Look College of Engineering  
 Texas A&M University • College Station, Texas 77843-3122  
 Phone (979) 845-3361 • Web site: <http://www.che.tamu.edu>

**M. Akbulut** • Ph.D., University of California, Santa Barbara, 2007  
*Nanotechnology, surface and interface science, drug delivery*

**P. Balbuena** • Ph.D., University of Texas, 1996, GPSA Professor  
*Molecular simulation and computational chemistry*

**D.B. Bukur** • Ph.D., U. of Minnesota, 1974, Joe M. Nesbitt Professor  
*Reaction engineering, math methods*

**T. Cagin** • Ph.D., Clemson University, 1988  
*Computational materials science and nanotechnology; functional materials for devices and sensors; surface and interface properties of materials*

**Z. Chen** • Ph.D., University of Illinois, Urbana-Champaign, 2006  
*Protein engineering and biomolecular engineering*

**Z. Cheng** • Ph.D., Princeton University, 1999  
*Nanotechnology*

**M. El-Halwagi** • Ph.D., Univ. of California, 1990  
 McFerrin Professor  
*Environmental remediation & benign processing, process design, integration and control*

**G. Froment** • Ph.D., University of Gent, Belgium, 1957  
*Kinetics, catalysis, and reaction engineering*

**C.J. Glover** • Ph.D. Rice University, 1974  
*Materials chemistry, synthesis, and characterization, transport, and interfacial phenomena*

**J. Hahn** • Ph.D., University of Texas, 2002, Ray Nesbitt Professor II & Assoc. Head  
*Systems biology, process systems engineering*

**M. Hahn** • Ph.D., Massachusetts Institute of Technology, 2004  
*Vocal fold tissue engineering; cell-biomaterial interactions*

**K.R. Hall** • Ph.D., Univ. of Oklahoma, 1967, Jack E. & Frances Brown Chair,  
 Deputy Director TEES  
*Process safety, thermodynamics*

**J.C. Holste** • Ph.D., Iowa State University, 1973  
*Thermodynamics*

**M.T. Holtzapple** • Ph.D., University of Pennsylvania, 1981  
*Biochemical*

**A. Jayaraman** • Ph.D., University of California, 1998, Ray Nesbitt Professor  
*Biomedical/biochemical*

**H.-K. Jeong** • Ph.D., University of Minnesota, 2004  
*Nanomaterials*

**K. Kao** • Ph.D., University of California, Los Angeles, 2005  
*Genomics, systems biology, and biotechnology*

**Y. Kuo** • Ph.D., Columbia University, 1979, Dow Professor  
*Microelectronics*

**C. Laird** • Ph.D., Carnegie Mellon University, 2006  
*Large-scale nonlinear optimization*

**J. Lutkenhaus** • Ph.D., Massachusetts Institute of Technology, 2007  
*Organic thin films and nanostructures*

**S. Mannan** • Ph.D., University of Oklahoma, 1986, Mike O'Connor Chair I  
 Director, Mary Kay O'Connor Process Safety Center, Process safety

**M. Pishko** • Ph.D., University of Texas at Austin, 1992, C.D. Holland Professor & Head  
*Biosensors, biomaterials, drug delivery*

**J. Seminario** • Ph.D., Southern Illinois University, 1988, Lanatter & Herbert Fox Professor  
*Molecular simulation and computational chemistry*

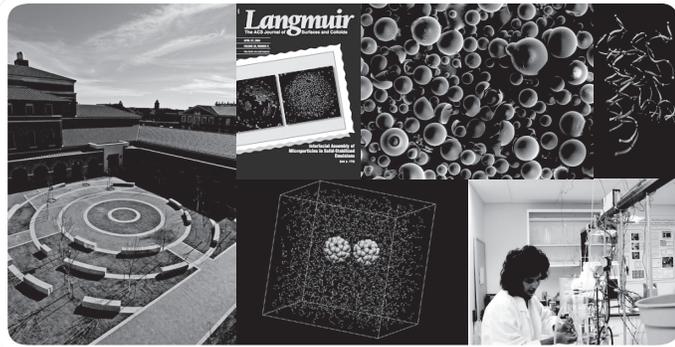
**D.F. Shantz** • Ph.D., University of Delaware, 2000, Neely Faculty Fellow,  
 Ray Nesbitt Professor III & Assoc. Head  
 Director, Materials Characterization Facility  
*Structure-property relationships of porous materials, synthesis of new porous solids*

**V. Ugaz** • Ph.D., Northwestern University, 1999, K.R. Hall Professor  
*Microfabricated Bioseparation Systems*

**S. Vaddiraju** • Ph.D., University of Louisville, 2006  
*Polymers*

**B. Wilhite** • Ph.D., University of Notre Dame, 2003  
*Reaction engineering*

**T.K. Wood** • Ph.D., North Carolina State University, 1991  
 Mike O'Connor Chair II  
*Green chemistry and bioremediation; biofilms*



## Texas Tech University

### Department of Chemical Engineering

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#### Contact Information

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Professor and Graduate Advisor  
greg.mckenna@ttu.edu



Texas Tech University  
Chemical Engineering Department  
P. O. Box: 43121  
Lubbock, TX 79409-3121

## GRADUATE PROGRAM IN CHEMICAL ENGINEERING

Texas Tech's Chemical Engineering Graduate Program offers an outstanding balance between theory and experiment and between research and practice. The Faculty represents a broad range of backgrounds that bring industrial, national laboratory and academic experiences to the future graduate student. External funding supports a diverse research portfolio including Polymer Science, Rheology and Materials Science, Process Control and Optimization, Computational Fluid Dynamics, Molecular Modeling, Reaction Engineering, Bioengineering and Nanobiotechnology.

**Key Features:** We have thirteen faculty members with significant industrial experience and national recognition within their fields of expertise. There is a Process Control and Optimization Consortium with participation from eight key chemical industries. In 2005 the Department spent over \$2.127 million in research expenditure to support graduate research projects. Based on an NSF published report, the Department ranks 46th among all the chemical engineering departments in the country based on research expenditure. Department has an NSF-funded Nanotechnology Interdisciplinary Research Team (NIRT) studying dynamic heterogeneity and the behavior of glass-forming materials at the nanoscale. More than 27,000 students attend classes in Lubbock on a 1,839 acre campus. Texas Tech University offers many cultural and entertainment programs, including nationally ranked football and basketball teams. Lubbock is a growing metropolitan city of more than 200,000 people and is located on top of the caprock on the South Plains of Texas. The city offers an upscale lifestyle that blends well with old fashioned Texas hospitality and Southwestern food and culture.

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## FACULTY



**Dr. Harvinder Gill**, PhD: Georgia Institute of Technology  
Assistant Professor

Research:  
Micro and nanosystems for drug and vaccine delivery; bionano-materials; mucosal vaccination; immunomodulation



**Dr. Micah Green**, PhD: Massachusetts Institute of Technology  
Assistant Professor

Research:  
Rheology, phase behavior, and applications of carbon nanotubes; multiscale modeling of complex fluids and biological materials.



**Dr. Ron Hedden**, PhD: Cornell University  
Associate Professor

Research:  
Synthesis and characterization of polymer networks and gels; development and characterization of polymers for microelectronics applications



**Dr. Karlene Hoo**, PhD: University of Notre Dame  
Professor

Research:  
Integration of process design with operability; Hemodynamics of venous vein and valve; Embedded control; Intelligent control; Systems engineering



**Dr. Naz Karim**, PhD: University of Manchester, UK  
Chairman and Professor

Research:  
Control and optimization of chemical and bio-processes; Bio-fuels production using recombinant microorganisms; Metabolic engineering glyco-proteins in CHO cell culture; Diabetic and cardiovascular diseases; Vaccine production for flu viruses



**Dr. Rajesh Khare**, PhD: University of Delaware  
Assistant Professor

Research:  
Nanofluidic devices for DNA separation and sequencing; Lubrication in human joints; Molecular dynamics and Monte Carlo simulations; Multiscale modeling methods; Properties of supercooled liquids and glassy polymers;



**Dr. Uzi Mann**, PhD: University of Wisconsin  
Professor

Research:  
Particulate technology and processes; Chemical reaction engineering; Chemical process analysis modeling and design; Formulation and synthesis of hollow micro and submicro particles; Biodiesel.



**Dr. Greg McKenna**, PhD: University of Utah  
Professor

Research:  
Small molecule interactions with glassy polymers; Torsion and normal force measurements; Nanorheology and nanomechanics; Melt and solution rheometry; Residual stresses in composite materials.



**Dr. Ranghunathan Rengasamy**, PhD: Purdue University  
Professor

Research:  
Fuel cell technology; Novel electrode and membrane fabrication for PEM fuel cells; Modeling, diagnostics and control of PEM and solid oxide fuel cells; Energy systems; Systems biology; Multi-Scale modeling and optimization; Controller performance assessment and process fault diagnosis.



**Dr. Sindee Simon**, PhD: Princeton University  
Professor

Research:  
The physics of the glass transition and structural recovery; Melting and T<sub>g</sub> at the nanoscale; Cure and properties of thermosetting resins; Measurement of the viscoelastic bulk modulus; Dilatometry and calorimetry.



**Dr. Siva Vanapalli**, PhD: University of Michigan  
Assistant Professor

Research:  
Mechanics of living cells; Biopolymer networks and single polymers; Integrated microsystems for cell and biomolecule analysis; Complex colloids for advanced materials; food emulsions, micro and submicro particles; Biodiesel.



**Dr. Mark Vaughn**, PhD: Texas A & M University  
Associate Professor

Research:  
Nitric oxide in the microcirculation; Membrane transport of small molecules; Transport and reaction in concentrated disperse system.



**Dr. Brandon Weeks**, PhD: Cambridge University, UK  
Assistant Professor

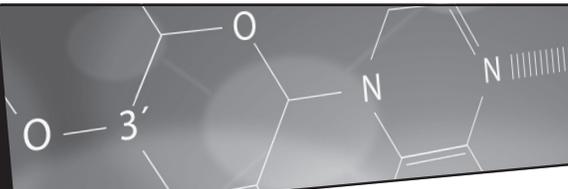
Research:  
Nanoscale phenomena in energetic materials including crystal growth, nanolithography, thermodynamics and kinetics; Atomic Force Microscopy and small angle x-ray scattering; Scanning probe instrument design and microscale sensors.



**Dr. Ted Wiesner**, PhD: Georgia Institute of Technology  
Associate Professor

Research:  
Capturing the energy generated by the human body to power implanted medical devices; Robust control of rate-adaptive cardiac pacemakers; Wastewater treatment for long-duration manned spaceflight; Computer-based training for engineers.

# 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 Florida*  
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

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[cheeddept@eng.utoledo.edu](mailto:cheeddept@eng.utoledo.edu)



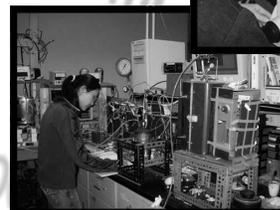
COLLEGE OF ENGINEERING  
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EN 583 0410

**Research Areas:**

- Batch Process Modeling, Optimization, Systems Engineering
- Biomaterials, Tissue Engineering
- Biomolecular Engineering, Cell Engineering, Natural Products
- Bionanotechnology, Biosensors, Smart Biopolymers Crystallization
- Energy, Environmental Engineering, Soft Electronics, Green Technologies, Fuel Processing, Fuel Cells
- Heterogeneous Catalysis, Nanocatalysis, Reaction Kinetics
- Mass Transfer with Chemical Reaction, Separation Process Modeling
- Metabolic Engineering, Systems Biology

The department offers **M. Eng.**, **M. Sci.**, and **Ph.D.** degrees in **Chemical Engineering** and a **Ph.D.** degree in **Biotechnology Engineering**. The curriculum emphasizes both rigor and breadth through core and elective coursework in addition to thesis research. In partnership with the School of Engineering, the department also offers **M. Eng.** and **M. Sci.** degrees in **Bioengineering**. The departmental track in **Cell and Bioprocess Engineering** focuses on bioprocess design and optimization with an emphasis on molecular and cellular processes.



**Department Faculty**

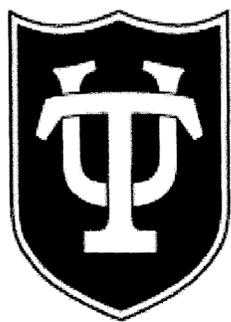
Linda Abriola, **Dean of School of Engineering** Ph.D., Princeton University  
 Nak-Ho Sung, **Department Chair** Ph.D., M.I.T.  
 Gregory D. Botsaris Ph.D., M.I.T.  
 Aurelie Edwards Ph.D., M.I.T.  
 Maria Flytzani-Stephanopoulos Ph.D., University of Minnesota  
 Christos Georgakis Ph.D., University of Minnesota  
 David L. Kaplan Ph.D., Syracuse University  
 Kyongbum Lee Ph.D., M.I.T.  
 Steven Matson Ph.D., University of Pennsylvania  
 Jerry H. Meldon Ph.D., M.I.T.  
 William Moomaw, Ph.D., M.I.T.  
 Matthew Panzer, Ph.D., University of Minnesota  
 Blaine Pfeifer Ph.D., Stanford University  
 Daniel R. Ryder Ph.D., Worcester Polytechnic Institute  
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 E-mail: [chbe@tufts.edu](mailto:chbe@tufts.edu)  
 Application materials and information  
 about the graduate studies at Tufts University  
 are available on the web  
 at <http://gradstudy.tufts.edu/>.



# Tulane University

*Department of Chemical and Biomolecular Engineering*

## **Faculty and Research Areas**

---

**Henry S. Ashbaugh** • *Classical Thermodynamics and Statistical Mechanics • Molecular Simulation • Solution Thermodynamics • Multi-Scale Modeling of Self-Assembly and Nanostructured Materials*

**Daniel C.R. DeKee** • *Rheology of Natural and Synthetic Polymers • Constitutive Equations • Transport Phenomena and Applied Mathematics*

**W.T. Godbey** • *Gene Delivery • Cellular Engineering • Molecular Aspects of Nonviral Transfection • Biomaterials*

**Vijay T. John** • *Biomimetic and Nanostructured Materials • Interfacial Phenomena • Polymer-Ceramic Composites • Surfactant Science*

**Victor J. Law** • *Modeling Environmental Systems • Nonlinear Optimization and Regression • Transport Phenomena • Numerical Methods*

**Brian S. Mitchell** • *Fiber Technology • Materials Processing • Composites*

**Kim C. O'Connor** • *Animal-Cell Technology • Organ/Tissue Regeneration • Recombinant Protein Expression*

**Kyriakos D. Papadopoulos** • *Colloid Stability • Coagulation • Transport of Multi-Phase Systems Through Porous Media • Colloidal Interactions*

**Noshir S. Pesika** • *Nanomaterial Synthesis and Characterization • Surface Functionalization and Rheology • Bio-inspired Materials • Surface Science; Electrochemistry.*

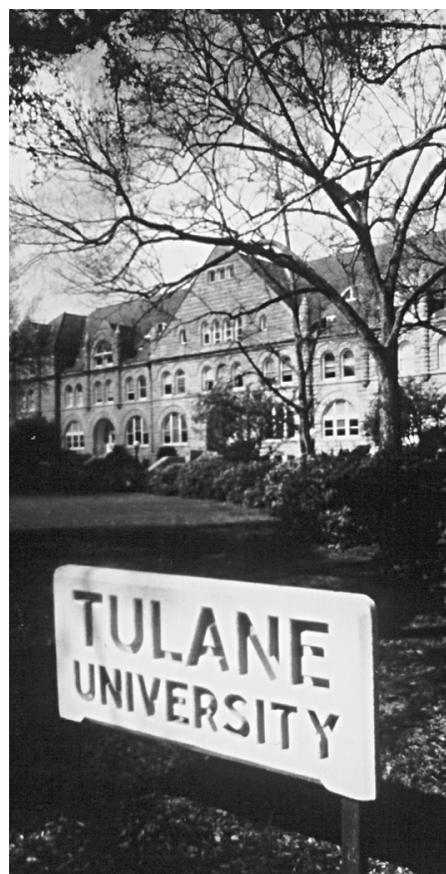
**Lawrence R. Pratt** • *Statistical Mechanics and Thermodynamics • Theory of Liquids and Solutions • Molecular Biology • Electrochemical Capacitors and Electrical Energy Storage Systems • Statistical Methods in Computational Science, Especially Molecular Simulation*

*For Additional Information, Please Contact*

---

### **Graduate Advisor**

**Department of Chemical and Biomolecular Engineering  
Tulane University • New Orleans, LA 70118  
Phone (504) 865-5772 • E-mail [chemeng@tulane.edu](mailto:chemeng@tulane.edu)**



Tulane is located in a quiet, residential area of New Orleans, approximately six miles from the world-famous French Quarter. The department currently enrolls approximately 40 full-time graduate students. Graduate fellowships include a tuition waiver plus stipend.

# Engineering the World

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### 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:

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- 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

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# Vanderbilt University



DEPARTMENT OF CHEMICAL AND BIOMOLECULAR ENGINEERING

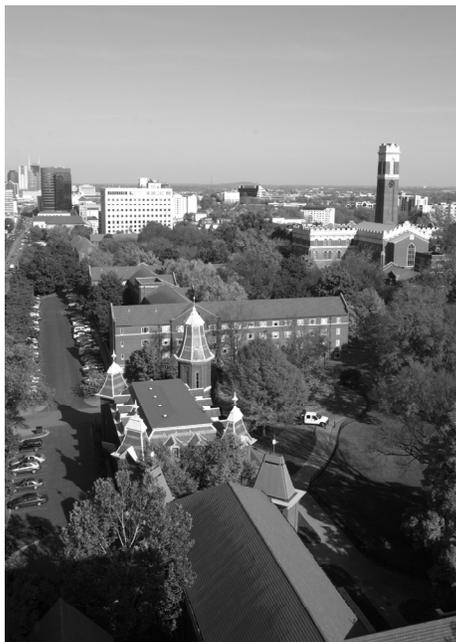
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422

**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**

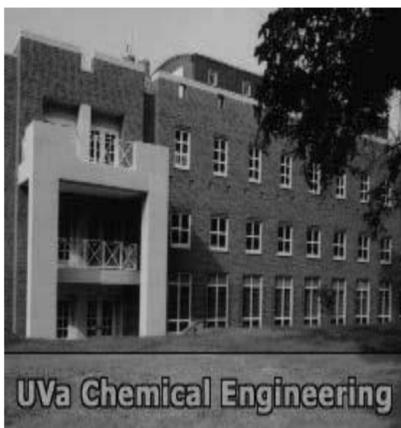
**Email: [chegrad@vanderbilt.edu](mailto:chegrad@vanderbilt.edu)**

*Chemical Engineering Education*

# University of Virginia



## Graduate Studies in Chemical Engineering



Graduate Admissions  
Dept. of Chemical Engineering  
102 Engineers' Way  
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University of Virginia  
Charlottesville, VA 22904-4741  
434-924-7778

E-mail:  
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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](mailto:chegrad@vt.edu) • <http://www.che.vt.edu>

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- Genetically Engineered Materials Science & Engineering Center (GEMSEC)
- Microscale Life Sciences Center (MLSC)
- National ESCA and Surface Analysis Center for Biomedical Problems (NESCA/BIO)
- National Nanotechnology Infrastructure Network (NNIN)

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- Photovoltaics and solar energy conversion
- Nuclear energy fuel reprocessing

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- Processes in living systems
- Biomolecular systems and processes

#### ***Molecular Aspects of Materials and Interfaces***

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- Colloids and complex fluids
- Biomaterials and biointerfaces
- Nanoscience and nanotechnology

#### ***Molecular/Organic Electronics***

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- Organic light emitting diodes
- Polymer physics
- Photonics

### **Core Faculty**

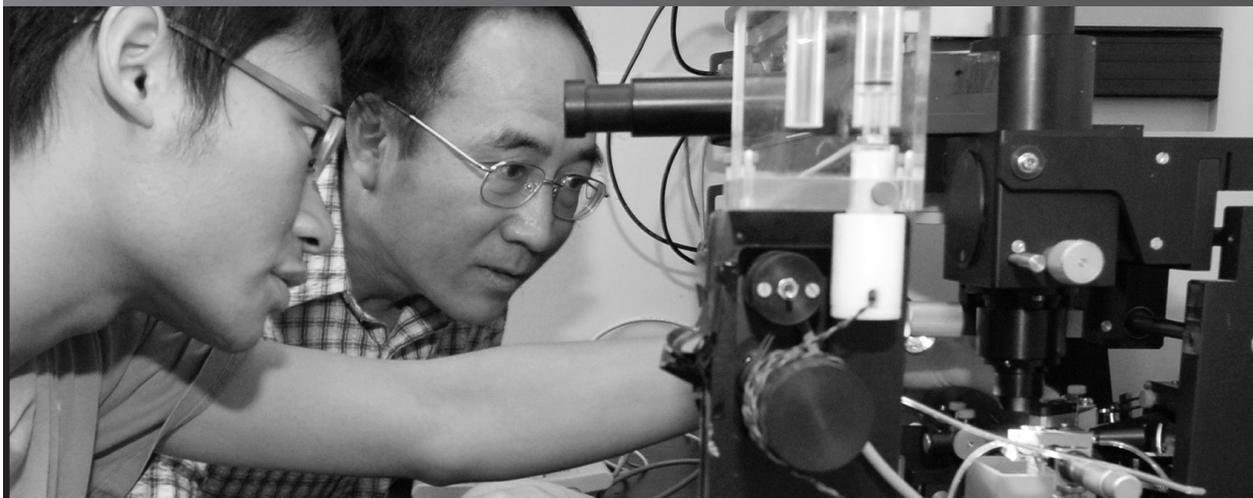
- Stuart Adler (UC Berkeley)
- François Baneyx (Texas–Austin)
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- David G. Castner (UC Berkeley)
- Hugh Hillhouse (Massachusetts)
- Bradley R. Holt (Wisconsin)
- Thomas A. Horbett (Washington)
- Samson A. Jenekhe (Minnesota)
- Shaoyi Jiang (Cornell)
- Mary E. Lidstrom (Wisconsin)
- René M. Overney (Basel, Switz.)
- W. Jim Pfaendtner (Northwestern)
- Daniilo Pozzo (Carnegie Mellon)
- Buddy D. Ratner (Brooklyn Poly.)
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- Daniel T. Schwartz (UC Davis)
- Hong Shen (Cornell)
- Eric M. Stuve (Stanford)
- Qiuming Yu (Cornell)

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Seattle, Washington 98195-1750

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- Bioseparations
- Biofilm engineering
- Cardiovascular systems
- Musculoskeletal dynamics
- Biomechanics

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- Environmental biotechnology

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The new Bioproducts, Sciences, and Engineering Laboratory on the Tri-Cities campus in Richland, Washington, allows researchers from WSU and the Pacific Northwest National Laboratory to work together to develop new solutions to the nation's energy problems.



### World class faculty

- Birgitte Ahring, Ph.D. Microbiology,  
University of Copenhagen
- Nehal Abu-Lail, Ph.D. Chemical Engineering,  
Worcester Polytechnic Institute
- Haluk Beyenal, Ph.D. Chemical Engineering,  
Hacettepe University
- Laurence Brewer, Ph.D. Physics,  
Massachusetts Institute of Technology
- Denny Davis, Ph.D. Agricultural Engineering,  
Cornell University
- Howard Davis, Ph.D. Biomechanics, University of Oregon
- Wenji Dong, Ph.D. Physical Chemistry,  
University of London, England
- Su Ha, Ph.D. Chemical Engineering, University of Illinois  
Urbana-Champaign
- Cornelius Ivory, Ph.D. Chemical Engineering,  
Princeton University
- KNona Liddell, Ph.D. Chemical Engineering,  
Iowa State University
- David Lin, Ph.D. Biomedical Engineering,  
Northwestern University
- Edward Pate, Ph.D., Mathematical Sciences  
Rensselaer Polytechnic Institute
- James Petersen, Ph.D. Chemical Engineering,  
Iowa State University
- Bernard Van Wie, Ph.D. Chemical Engineering,  
Oklahoma University
- Anita Vasavada, Ph.D. Biomedical Engineering,  
Northwestern University
- Yong Wang, Ph.D., Chemical Engineering  
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Energy, Environmental and Chemical Engineering*

**Washington**

**University in St. Louis**

**Masters  
and  
Ph.D  
Programs**



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- 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**  
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- > Biotechnology and Biochemical Engineering
- > Catalysis
- > Composite Materials
- > Fuel Cells
- > Green Reaction Engineering
- > Interfacial Phenomena/Membrane Technology
- > Polymer engineering
- > Process Control and Statistics
- > Separation Processes

### **RESEARCH GROUPS AND PROFESSORS:**

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*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](mailto:gradinfo.che@uwaterloo.ca)  
or visit our website at <http://cape.uwaterloo.ca>

# ChE / MSE WAYNE STATE UNIVERSITY

M.S. and Ph.D. in  
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## Faculty and their Research

**Sandro R. P. da Rocha, Ph.D., U of Texas at Austin** • nanomaterials for drug delivery; inhalation aerosols; colloids in conventional and compressible media; computational methods.

**Yinlun Huang, Ph.D., Kansas State** • multi-scale complex systems design and optimization; engineering sustainability and decision making; computational nanomaterial design.

**Rangaramanujam Kannan, Ph.D., Caltech** • nanomaterials for targeted drug delivery; polymer processing, rheo-optics; polymer nanocomposites; dendrimers for drug delivery.

**Joseph Louvar, Ph.D., Wayne State** • chemical process safety; shortstopping runaway reactions via CFD models; characterizing runaway reactions.

**Charles Manke, (Department Chair) Ph.D., California, Berkley** • simulations of polymers and biomolecules; polymer rheology and processing in supercritical fluids.

**Guangzhao Mao, Ph.D., U of Minnesota** • directed self-assembly and crystallization; SPM imaging of soft materials; hybrid nanomaterials; gene delivery.

**Howard Matthew, Ph.D., Wayne State** • cell and tissue engineering; polymeric biomaterials; bioactive polysaccharides; stem cells and regenerative medicine.

**Simon Ng, Ph.D., (Assoc. Dean for Research) U of Michigan** • heterogeneous catalysis; biomaterials and biocompatibility; Biodiesel; gas and chemical sensors, alternative energy technologies.

**Jeffrey Potoff, Ph.D., Cornell** • molecular modeling; simulation and thermodynamics; membrane fusion; membrane-protein interactions; energetic materials.

**Susil Putatunda, Ph.D., IIT Bombay** • fatigue & fracture; alloy development & microstructure property relationship; metals and magnetic materials.

**Erhard Rothe, Ph.D., U of Michigan** • surface modification with UV laser-light; analysis of supercritical CO<sub>2</sub> by laser light; nano-sized surface features.

**Steven Salley, Ph.D., U of Detroit** • biochemical / biomedical engineering; alternative energy technologies.

**Gina Shreve, Ph.D., U of Michigan** • biocatalysis: biosensor molecular simulation; in situ and ex situ environmental bioremediation.

**Dennis Corrigan, (Research Professor) Ph.D., U of Wisconsin** • electrochemistry, batteries; fuel cells, and supercapacitors; electric and hybrid vehicle applications.

**Contact:** Department of Chemical Engineering and Materials Science, Wayne State University, 5050 Anthony Wayne Dr., Detroit, MI 48202 • Phone: 313-577-3800 / 3837 • [chegrad@eng.wayne.edu](mailto:chegrad@eng.wayne.edu)



<http://www.eng.wayne.edu/che>

## Faculty

**Sushant Agarwal**  
West Virginia University

**Brian J. Anderson**  
Massachusetts Institute of  
Technology

**Debangsu Bhattacharyya**  
Clarkson University

**Eugene V. Cilento, Dean**  
University of Cincinnati

**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. Shaiwitz**  
Carnegie Mellon University

**Alfred H. Stiller**  
University of Cincinnati

**Charter D. Stinespring**  
West Virginia University

**Richard Turton**  
Oregon State University

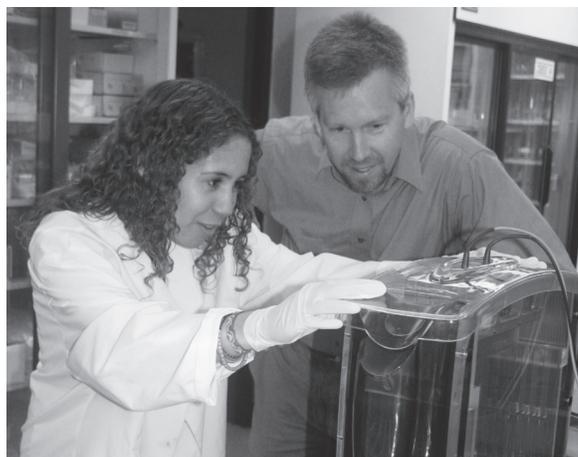
**Ray Y. K. Yang**  
Princeton University

**John W. Zondlo**  
Carnegie Mellon University



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Particle Coating / Agglomeration  
Polymer Rheology  
Separation Processes

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Fellowships  
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## 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

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**DANIEL J. KLINGENBERG** • Colloid science, complex fluids, suspension rheology

**THOMAS F. KUECH** • Semiconductor and advanced materials processing, solid-state, electronic, and nanostructured materials, interface science, solar energy

**DAVID M. LYNN** • Polymer synthesis, biomaterials, functional materials, gene and drug delivery, controlled release, high-throughput synthesis/screening

**CHRISTOS T. MARAVELIAS** • Production planning and scheduling, supply chain management, optimization under uncertainty, process synthesis, systems biology

**MANOS MAVRIKAKIS** • Thermodynamics, kinetics and catalysis, surface science, computational chemistry, electronic materials, fuel cells, hydrogen economy

**REGINA M. MURPHY** • Biomedical engineering, protein-protein interactions, neurodegenerative disorders



Michael Forster-Rothbart, UW-Madison University Communications

**PAUL F. NEALEY** • Polymers, directed assembly, nanofabrication, cell-substrate interactions

**SEAN P. PALECEK** • Stem cell engineering, cell adhesion, cell signaling

**BRIAN F. PFLEGER** • Synthetic biology, biotechnology, protein engineering, sustainable chemical production

**JAMES B. RAWLINGS** • Chemical reaction engineering, process modeling, dynamics, and control, statistical and computational methods in systems biology

**JENNIFER L. REED** • Systems biology, metabolic model development and analysis, metabolic engineering

**THATCHER W. ROOT** • Green chemistry, renewable resources, catalysis, solid-state NMR

**ERIC V. SHUSTA** • Drug delivery, protein engineering, biopharmaceutical design

**ROSS E. SWANEY** • Process design, synthesis, modeling, and optimization

**JOHN YIN** • Systems biology, virus-cell interactions, immunology, microfluidics

### For more information, please contact:

Graduate Program Office  
Department of Chemical & Biological Engineering  
University of Wisconsin-Madison  
1415 Engineering Drive  
Madison, Wisconsin 53706-1607  
U.S.A.

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*William M. Clark, PhD, Rice University*

**Catalysis and Reaction Engineering  
as Applied to Fuel Cells and Hydrogen**  
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*N. Aaron Deskins, PhD, Purdue University*

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**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

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- **Thomas Graedel** (School of Forestry & Environmental Studies)
- **Kurt Zilm** (Chemistry)
- **Mark Saltzman** (Biomedical Engineering)



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# BRIGHAM YOUNG UNIVERSITY

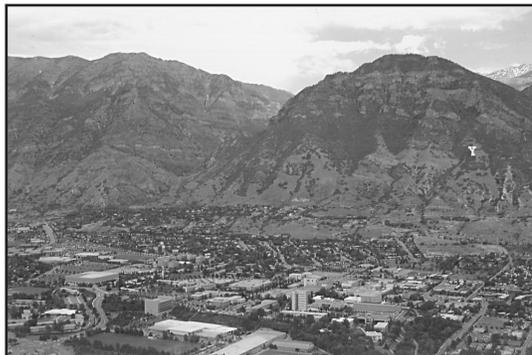
## *Graduate Studies in Chemical Engineering*

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

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BYU

# BUCKNELL UNIVERSITY

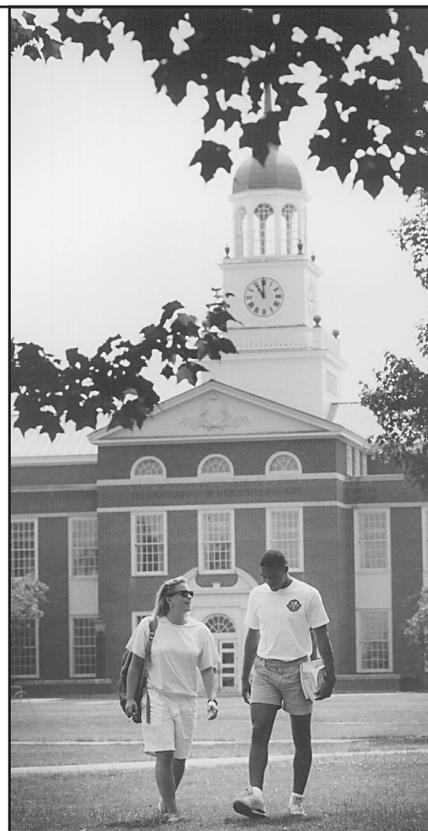
Master of Science in Chemical Engineering

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For further information, contact  
 Professor Kat Wakabayashi  
 Department of Chemical Engineering  
 Bucknell University, Lewisburg, PA 17837  
 Phone 570-577-1114  
[kat.wakabayashi@bucknell.edu](mailto: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 State)  
*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*
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*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*





# CLARKSON UNIVERSITY

## Department of Chemical & Biomolecular Engineering Graduate Study in Chemical Engineering (M.S. and Ph.D. Degrees)

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### Research collaboration is enhanced through the following University centers:

- ◆ Center for Advanced Materials Processing (CAMP)
- ◆ Center for Air Resources Engineering & Science (CARES)
- ◆ Center for Rehabilitation Engineering, Science and Technology (CREST)
- ◆ Center for Sustainable Energy Systems (CSES)

### For information and applications, apply to:

Graduate Committee  
Department of Chemical & Biomolecular Engineering  
Clarkson University, Potsdam, NY 13699-5705  
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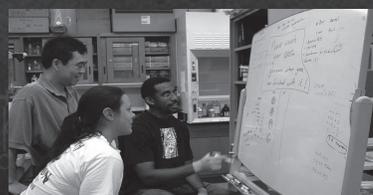
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#### Research Areas

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- Polymers and Complex Fluids
- Multiscale Theory, Modeling, and Simulation



#### Faculty

- Rufina Alamo (University of Madrid)
- Ravindran Chella (University of Massachusetts)
- John Collier (Case Western Reserve University)
- Wright Finney (Florida State University)
- Samuel Grant (University of Illinois)
- Jingjiao Guan (Ohio State University)
- Egwu Kalu (Texas A&M University)
- Milen Kostov (Pennsylvania State University)
- Bruce Locke (North Carolina State University)
- Teng Ma (Ohio State University)
- Anant Paravastu (University of California, Berkeley)
- Hyun-Ok-Park (University of Florida)
- Subramanian Ramakrishnan (University of Illinois)
- Loren Schreiber (California Institute of Technology)
- Theo Siegrist (ETH,Zurich)
- John Telotte (University of Florida)

#### For more information contact:

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**John P. Tharakan, Professor** • PhD, University of California, San Diego

*Bioprocess engineering • protein separations • biological hazardous waste management • bio-environmental engineering*

For further information, contact \_\_\_\_\_

Director of Graduate Studies • Department of Chemical Engineering

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**Eric Aston** *Surface Science, Thermodynamics, Microelectronics*

**David Drown** *Process Design, Computer Application Modeling, Process Economics and Optimization-Emphasis on Food Processing*

**Dean Edwards** *Autonomous Vehicles, Battery research*

**Lou Edwards** *Computer Aided Process Design, Systems Analysis, Pulp/Paper Engineering, Numerical Methods and Optimization*

**Jin Park** *Chemical Reaction Analysis and Catalysis, Laboratory Reactor Development, Thermal Plasma Systems*

**Supathorn "Supy" Phongikaroon** *Nuclear Fuel Cycle, Spent Fuel Treatment (Idaho Falls campus)*

**Aaron Thomas** *Transport Phenomena, Fluid Flow, Separations Magnetohydrodynamics*

**Vivek Utgikar** *Environmental Fluid Dynamics, Chem/Bio Remediation, Kinetics (Idaho Falls Campus)*

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- ◆ Heterogeneous Catalysis, Reaction Engineering
- ◆ Air Quality Modeling, Fluidization Engineering
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• Isolated nanoparticles and supported nanoparticles  
• Environmental catalysis

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• Multivariate statistical analysis  
• Process control and optimization  
• Computer assisted process design

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• Biomolecular, cellular and metabolic engineering  
• Development and optimization of novel protein expression systems  
• Recombinant protein production processes

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• Virus, protein and vaccine production

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Louvain-La-Neuve, Belgium)  
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• Separation of liquid and gas mixtures  
• Membrane technology

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• Catalytic membranes and fuel cells  
• Industrial catalysis

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• Numerical simulation of cooling processes  
• Thermo-electrical simulation

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(Ph.D. INPL Nancy)

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• Wet oxidation  
• Flow instrumentation

### Frej Mighri

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• Polymer processing (extrusion, injection molding,...)  
• Rheology and polymer blends compounding  
• Functional polymer blends processing  
• In-situ monitoring of polymer processing

### Denis Rodrigue

(Ph.D. Université de Sherbrooke)

denis.rodrigue@gch.ulaval.ca 418 656-2903  
• Transport phenomena  
• Rheology  
• Polymeric foams

## Research Areas

### Graduate Studies M.Sc. and Ph.D.

#### Additional information :

#### Head of Graduate Programs Frej Mighri

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Ching-An Peng; Professor • PhD, University of Michigan, 1995

## **Chemical process safety**

Daniel A. Crowl; Professor • PhD, Illinois, 1975

## **Demixing-polymerization, polymer materials**

Gerard T. Caneba; Professor • PhD, California-Berkeley, 1985

## **Electrocatalysis, fuel cells**

Wenzhen Li; Assistant Professor • PhD, Dalian Inst. of Chemical Physics of Chinese Academy of Science, 2004

## **Environmental and biochemical engineering**

David R. Shonnard; Professor • PhD, California-Davis, 1991

## **Environmental reaction engineering**

Jason M. Keith; Associate Professor • PhD, Notre Dame, 2000

## **Environmental thermodynamics**

Tony N. Rogers; Associate Professor • PhD, Michigan Tech, 1994

## **Materials Utilization**

John F. Sandell; Associate Professor • PhD, Michigan Tech, 1995

## **Particulate processing, size reductions, solid waste**

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Houghton, MI 49931-1295  
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## **Polymer rheology, flow instabilities, complex fluids**

Faith A. Morrison; Associate Professor • PhD, Massachusetts-Amherst, 1988

## **Process control, neural networks, fuzzy logic control**

Tomas B. Co; Associate Professor • PhD, Massachusetts-Amherst, 1988

## **Reactor design, thermodynamics, materials**

Michael E. Mullins; Professor • PhD, U. of Rochester, 1983

## **Technical Communications**

M. Sean Clancey; Lecturer • PhD, Michigan Tech, 1998

## **Electrokinetics, Medical Microdevices**

Adrienne Minerick • PhD, University of Notre Dame, 2003

## **Biofuels, Modeling, Bioinformatics**

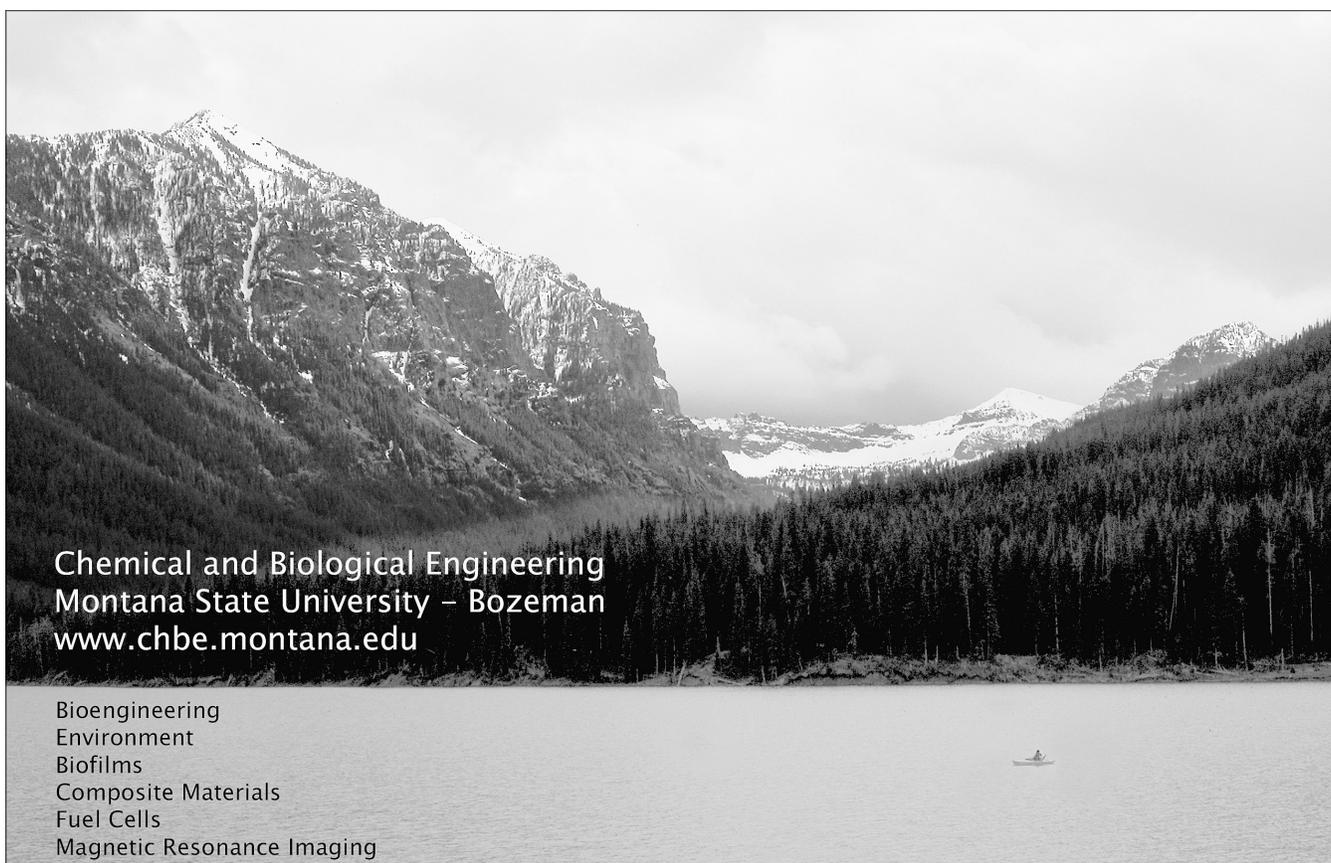
Wen Zhou • PhD, University of California, Los Angeles, 2006

## **Bioseparations, Virus Removal & Purification, and Biosensors**

Caryn Heldt • PhD, North Carolina State University, 2008

## **Metals Bioprocessing, Separations**

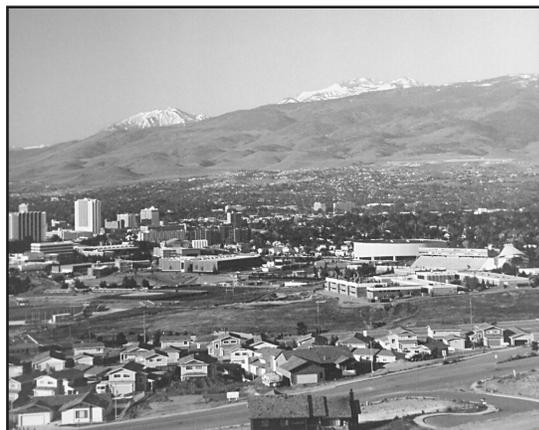
Timothy Eisele • PhD, Michigan Technological University, 1992



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Molecular Simulation	Renewable Energy
Fluidization	Nanotechnology

## Faculty

Charles J. Coronella (Univ. of Utah)  
 Alan Fuchs, Chair (Tufts)  
 Hongfei Lin (Louisiana State University)  
 Vaidyanathan Subramanian (Univ. of Notre Dame)  
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*Biointerfacial Phenomena*  
*Bioengineering Ethics*  
**Chih-hung Chang**  
*Semiconductor Materials, Nanotechnology*  
*Integrated Chemical Systems*  
**Mark Dolan**  
*Biological Remediation of Groundwater*  
**Gregory Herman**  
*Microreactor Engineering, Solar P.V. Cells, Catalysis*  
**Adam Higgins**  
*Cell & Tissue Preservation*  
**Goran Jovanovic**  
*Microscale Chemical & Biosensor Devices*  
*Nanotechnology*  
**Christine Kelly**  
*Biotechnology*  
**Shoichi Kimura**  
*Reaction Engineering*  
*Bioceramics*  
**Milo Koretsky**  
*Electronic Materials Processing*  
*Nanotechnology*

**Keith Levien**  
*Process Optimization & Control*  
*Supercritical Fluids Technology*  
**Joseph McGuire**  
*Biointerfacial Phenomena, Biomaterials*  
**Jeff Nason**  
*Physical/Chemical Processes for Water and Wastewater Treatment*  
**Skip Rochefort**  
*Polymer Processing, Education & Outreach*  
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*Biochemical Reaction, Engineering*  
**Lewis Semprini**  
*Biological Remediation of Groundwater*  
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*Transport Theory & Applications*  
*Stochastic Subsurface Hydrology*  
**Kenneth Williamson**  
*Bioengineering, Environmental Systems*  
**Brian Wood**  
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Interfacial Phenomena, Separations

**R.S. Artigue, D.E., Tulane**  
Process Control, Micro/Ultrafiltration

**D.G. Coronell, Ph.D., MIT**  
Reactor Engineering, Materials,  
Computation

**M.H. Hariri, Ph.D., Manchester, U.K.**  
Energy, Environment and Safety

**K.H. Henthorn, Ph.D., Purdue**  
Particle Technology, Microfluidics

**S.J. McClellan, Ph.D., Purdue**  
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**S.G. Sauer, Ph.D., Rice**  
Thermodynamics

**A. Serbezov, Ph.D., Rochester**  
Adsorption, Process Control

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J.A. Caskey, Ph.D., Clemson

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N.E. Moore, Ph.D., Purdue



## Faculty and Research Areas

**Sookie S. Bang** (PhD, University of California, Davis)  
*Biocatalyst, bio-materials, genomics, microbiology*

**Kenneth M. Benjamin** (PhD, University of Michigan)  
*Molecular modeling, bioenergy, supercritical/ionic fluids*

**Lew P. Christopher** (PhD, Bulgarian Ac. of Sci., Bulgaria)  
*Center for Bioprocessing R&D: biomass to fuels/products*

**David J. Dixon** (PhD, University of Texas, Austin)  
*Supercritical fluids, membranes, biomass pretreatment*

**Patrick C. Gilcrease** (PhD, Colorado State University)  
*Biomass conversion, fermentation, coal-bed biomethane*

**Jason C. Hower** (PhD, University of Washington)  
*Molecular modeling, bio-interfacial phenomena, biosensors*

**Todd J. Menkhaus** (PhD, Iowa State University)  
*Bioseparations, nanofelts, membranes, biomass processing*

**Jan A. Puszynski** (PhD, Inst. of Chem. Tech., Czech. Rep)  
*Nanotechnology, combustion synthesis, energetic materials*

**David R. Salem** (PhD, University of Manchester, U.K.)  
*Polymers, bio/nano composites, p-s-p relationships*

**Rajesh K. Sani** (PhD, Panjam University, India)  
*Bioremediation, metabolic engineering, biotechnology*

**Rajesh V. Shende** (PhD, University of Mumbai, India)  
*Sustainable energy, nanomaterials, thin films, sensors*

**Robb M. Winter** (PhD, University of Utah)  
*Polymer composites, nano-mechanics, surface engineering*

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Dacheng Ren  
Ashok S. Sangani  
Radhakrishna Sureshkumar  
Lawrence L. Tavlarides

### RESEARCH AREAS:

Biomaterials  
Biomechanics  
Complex Fluids  
Drug Delivery  
Multiscale Simulation  
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Polymers  
Process Analysis  
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### Research Areas    Faculty

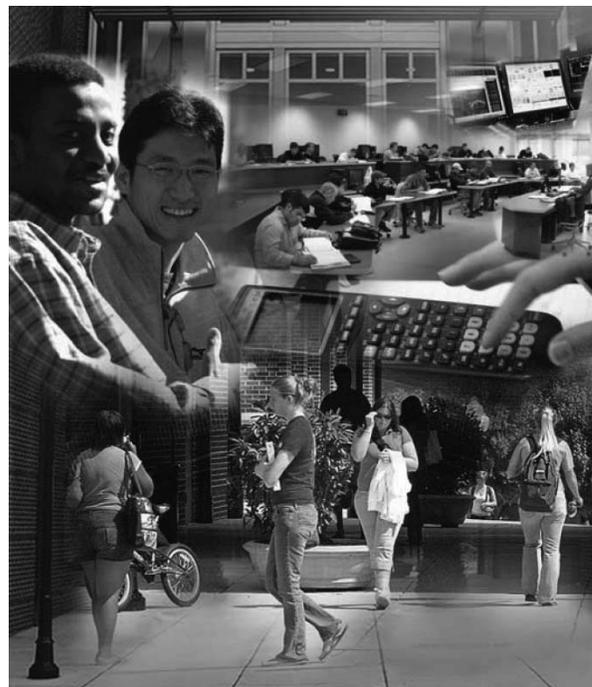
Renewable Fuels    Jim Henry, Ph.D., P.E., 1970, Princeton  
Process Controls    Frank Jones, Ph.D., P.E., 1991, Drexel  
BioEngineering    Tricia Thomas, Ph.D., 1998, CMU

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Natural Gas Engineering  
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*Reservoir Engineering and Production*

#### J. L. CHISHOLM

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#### W. A. HEENAN

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#### A. A. PILEHVARI

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#### H. A. DUARTE

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*Thermodynamics, Physical Property, Measurements,  
Process Simulation*

#### P. L. Mills

D.Sc., Washington University in St. Louis  
*Reaction Engineering and Process Science*



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*For more information, contact:*

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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  
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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 4<sup>th</sup> 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,  
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[che@csuohio.edu](mailto:che@csuohio.edu)  
website: [http://www.csuohio.edu/chemical\\_engineering/](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

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chemical\\_and\\_materials/index.php](http://www.udayton.edu/engineering/chemical_and_materials/index.php)



## 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:

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*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>