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**Visual Encyclopedia of Chemical Engineering Equipment**

The Visual Encyclopedia of Chemical Engineering Equipment, now available free online at <encyclopedia.che.engin.umich.edu>, has been developed over the past 20 years to help students and faculty learn how chemical engineering equipment works. More than 100 kinds of equipment are covered, and for each piece students can see photographs, drawings, animations, and videos that demonstrate what the equipment looks like and how it works. Advantages and disadvantages of various types of equipment are also included, as well as visuals of installed equipment.

You can implement the encyclopedia into your courses to give your students a depth beyond the fundamentals:

- Incorporate graphics, animations, and videos from the encyclopedia into your class presentations, with the reference included.
- Use the encyclopedia directly in lectures to familiarize your students with it.
- If you are using the 3rd edition of Felder and Rousseau\(^\text{11}\) or the 4th edition of Fogler\(^\text{21}\) take advantage of the references that already exist.
- Include a link to the encyclopedia in your class website.
- Supplement your homework assignments by requiring students to search the encyclopedia and answer simple questions about equipment.
- Add simple extra credit problems on exams based on the encyclopedia, to give students an added incentive to explore it.
- If your course projects include equipment, require students to use the encyclopedia as a reference.
- Encourage students in design courses to refer to the encyclopedia to have a better understanding of the equipment they are designing.

**REFERENCES**


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This one-page column presents practical teaching, advising, and diversity tips in sufficient detail that others can adopt the tip. Focus on the teaching method, not content. The column should be maximum 550 words, but subtract 50 words for each figure or table. Submit as a Word file to Phil Wankat <wankat@ecn.purdue.edu>.
THE VALUE OF AN INDUSTRIAL INTERNSHIP FOR A GRADUATE STUDENT EDUCATION

GREGORY S. HONDA,\textsuperscript{1} JORGE H. PAZMÍNO,\textsuperscript{2} DANIEL A. HICKMAN,\textsuperscript{3} AND ARVIND VARMA\textsuperscript{1}

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For major corporations, a portfolio of internal research and development balanced by external engagement with academia provides a competitive advantage. One method by which this is accomplished is through internships offered to Ph.D. graduate students. The intern directly addresses research questions related to a current manufacturing process or ongoing development program through the completion of a collaborative project while he/she gains a background in industrial research that, with successful recruiting, can be leveraged to solve future challenges for the company. At the same time, the academic institution strengthens its ties with the corporation, opening the opportunity for further interactions with the school and its research groups. Typically, an internship may be within the student’s field, but not the student’s expertise or thesis. In such a circumstance, while the student may learn about a different area, the internship would not contribute to his/her thesis. A better option is for the assigned project to be within the scope of the student’s thesis, as in the internship described in this work.

In this particular case, the internship came about as the result of an ongoing collaboration to study trickle bed reactor hydrodynamics between Dr. Arvind Varma’s research group at Purdue University and the Reaction Engineering group at Dow, a part of Engineering and Process Sciences (E&P) in Core R&D. The work completed during this collaboration comprises the graduate student’s Ph.D. thesis on trickle bed hydrodynamics, with a focus on the effect of catalyst support properties. Prior to beginning the internship, the student had evaluated the effect of catalyst support particle size distribution on the hydrodynamics under trickling flow.\textsuperscript{11} While gaining insight into hydrodynamics at the lab scale provides useful information, for results to be relevant to industry, it is important to understand to what degree hydrodynamics vary with vessel scale.

\begin{flushright}
\textbf{Greg Honda} is a chemical engineering Ph.D. candidate in Dr. Arvind Varma’s research group at Purdue University. He received his B.S. in chemical engineering from the University of Connecticut with honors in 2010. His research interests are in reaction engineering, including micro-reactors and trickle bed reactors.

\textbf{Jorge Pazmíno} is an associate engineer at the Reaction Engineering group in Core R&D at The Dow Chemical Company. Jorge obtained his Ph.D. from Purdue University in 2011 in the area of heterogeneous catalysis. During his time at Dow, he has supported several businesses with reactor and kinetic modeling, process validation from lab scale experiments, scaling up new technologies for oil extraction, and tool optimization for predicting catalyst deactivation. His interests are aligned with deriving kinetic models from experimental data, catalyst screening, and characterization.

\textbf{Dan Hickman} is a fellow in the Reaction Engineering group in Core R&D at The Dow Chemical Company. Dan has been a subject matter expert and technical leader in reaction engineering and process development for numerous reaction systems across a variety of Dow businesses and technologies. In addition to holding 11 patents, Dan’s contributions at Dow include designing reactors for three commercial processes—two currently in operation and a third under construction.

\textbf{Arvind Varma} is R. Games Slayter Distinguished Professor and Jay & Cynthia Ihlenfeld Head, School of Chemical Engineering at Purdue University. Author of more than 250 archival journal articles and three books, he has research interests in chemical and catalytic reaction engineering and new energy sources. He has received a number of recognitions for his research and teaching, including AIChE’s R. H. Wilhelm and Warren K. Lewis Awards, and serves as the founding editor (1996-present) of the Cambridge Series in Chemical Engineering.
\end{flushright}
Trickle bed reactors are used throughout industry for hydrodesulfurization, hydrogenation, and selective oxidation reactions and are characterized by cocurrent downflow of gas and liquid reactants through a packed bed of catalyst. The multiphase flow results in hydrodynamics that impact reactor performance. Therefore, understanding how the hydrodynamics change as a function of different bed and operating variables, and determining how these interactions vary with vessel scale, can increase economic profit. In the trickle flow regime, hydrodynamics are described by the parameters of liquid holdup and pressure drop, which are impacted by changes in gas, liquid, and bed properties. The effect of these variables may be evaluated at room temperature and pressure with air and water as fluids and with no reaction. Generally, observations are expected to be independent of scale if the ratio of vessel to particle diameter is greater than 20, which would indicate the absence of wall effects. However, prior results internal to Dow had shown a decrease in pressure drop with increase in vessel diameter, even though this criteria was satisfied. Therefore, the technical goal of the internship was to evaluate the effect of vessel diameter on the hydrodynamics under trickling flow for beds packed with activated carbon. Because the internship arose from an ongoing collaboration, the student had the opportunity to pursue work related directly to his thesis, which is mutually beneficial to the student and the company.

**PRIOR EXPERIENCE GAINED ON CAMPUS**

Beyond general exposure to the variety of reactor types within the graduate reaction engineering course, the primary learning the student brought to the internship came from practical aspects of the lab work and a deep understanding of the literature associated with the project. This included criteria regarding reactor sizing, methods for packing of catalyst in trickle beds, and knowledge of the pre-wetting methods necessary to achieve reproducible results.

**PROJECT OVERSIGHT**

During the course of the internship, the student was in regular communication with his direct supervisor, who set up initial orientation and training, checked on the student’s progress, and acted as liaison in meeting appropriate personnel. Additional project oversight came from weekly meetings with the student’s industry advisor, who was also serving on the student’s thesis committee and was the primary contact throughout the collaboration. Lastly, the student submitted an internal report at the end of the internship and presented his work to E&PS employees. While input was provided to the student in order to meet project goals, the overall effort was largely self-guided because of the familiarity the student already had with the project. Thus, the internship in this case provided a more realistic work experience where the student was responsible for the direction and completion of the project.

**Figure 1. Diagram of the setup including (1) column, (2) air supply, (3) air flow control, (4) water flow control, (5) pump, and (6) liquid reservoir. The system is analogous for 1/2” and 6” ID vessels. Boxes with a “P” indicate pressure transducers.**
REVIEW OF PREVIOUS WORK AT DOW AND PROJECT DEFINITION

Before starting the internship, while the issue regarding the effect of scale was known to the student, the details of the project and previous internal efforts were not provided due to intellectual property issues. Once at Dow, the intern had to determine the direction of the project by evaluating all of the available resources, including Dow proprietary material and personnel. The review of intellectual resources allowed the student to determine that the previous researchers used an inconsistent pre-wetting procedure for the activated carbon-packed bed in attaining the earlier results.

SAFETY REVIEW AND EXPERIMENTAL PROCEDURE

Concurrently with the problem review, the student worked with the lab technician to design and build the experimental setup and with network and communication services to set up the instrumentation. Relative to academic research, industry requires working with a greater number of other employees. While their expertise is available, competing priorities required development of soft skills by the intern. While project setup was ongoing, the student initiated the management of change (MOC) process. The MOC process guides the safety review for a project to ensure safe operation. Although the experiments used air and water, a thorough safety review was required because the setup was new. In general, safety practices, such as the MOC process, are more thorough in industry, where methods learned in the plant may be applied in the lab. Appropriate safety practices and review provide opportunity not only to make a project safer but also more effective. The safety practices learned in an industrial internship can be applied by the student in his or her research group and school.

The diagram of the resulting setup after the MOC and construction were completed is shown in Figure 1. Manual control valves controlled the air and water flow, and flow meters measured the flow rates. Air passed through the bed and was vented to the atmosphere, while water was recycled from a reservoir. Two columns were used, one with a 1/2” diameter and another with a 6” diameter. In the 6” column, water passed through a distributor while in the 1/2” column, water was introduced by a 1/4” tube in the center of the column. Columns were packed with 20-50 mesh Nuchar RGC activated carbon. The Sauter mean diameter of the particles was 620 µm. The void fraction was determined to be 0.370 ±0.006 for both columns, based on the envelope volume and mass of the particles added to the columns. The columns were clear acrylic to visually monitor flow regime, which is the contacting pattern of the gas and liquid flowing through the column. In this work, all data were gathered in the trickle flow regime, where gas is continuous, and liquid flows as a stable thin film over the particles. Phenomenological models for trickle flow define a hydrodynamic state based on bed and fluid variables. For a given state, a specific pressure drop and liquid holdup are defined. Experimental measurement of the pressure drop for a set of operating variables defines the hydrodynamic state. In this study, pressure drop was monitored by a differential pressure transducer mounted across a 24” section of the bed. Comparison of pressure drops will verify whether or not hydrodynamics are affected by vessel diameter.

With the setup in place, an appropriate pre-wetting procedure was developed. The activated carbon used in this study was not readily wetted by the water when flowing from top down both with and without air flowing. With the air flowing, the water did not uniformly wet the packed bed of particles. Without air flowing, the liquid would not penetrate the bed, instead flooding the area above it. To overcome this, a new pre-wetting procedure was developed (Figure 2). After flooding water above the bed with the outlet closed and the air line
opened to vent, air was introduced to force the liquid slug through the bed, thereby uniformly wetting the particles. After this procedure, air was introduced at a fixed superficial velocity, and the liquid flow rate was increased until pulsing flow was observed. The liquid flow rate was then decreased until the trickling flow regime was reached, where data were then gathered with decreasing and increasing liquid flow rate.

TECHNICAL RESULTS

Experimental results comparing dimensionless pressure drop, $\psi_L$, between the 1/2" and 6" ID columns packed with the activated carbon are shown in Figures 3. For a given gas and

\begin{align*}
\text{Figures 3. Dimensionless pressure drop for the 1/2" (empty symbol) and 6" (filled symbol) columns with varying $v_L$ for a fixed $v_c$:} & \\
\text{a) 310 mm/s, b) 220 mm/s, c) 110 mm/s,} & \\
\text{d) 60 mm/s, and e) 30 mm/s.}
\end{align*}
liquid superficial velocity \((v_G \text{ and } v_L, \text{ respectively})\), pressure drop was slightly lower (by only ~5%) in the 6" ID vessel than the 1/2" ID vessel. This is in contrast to previous work at Dow, which at \(v_G = 10 \text{ mm/s} \) and \(v_L = 4 \text{ mm/s} \) had observed a 40% decrease in dimensionless pressure drop between the 1/2" and 6" ID vessels (from 5.2 to 3.1, respectively). Relative to this observation, the difference between the pressure drop in the 6" and 1/2" ID vessels evaluated in this study is minor. For trickle bed reactors, wall effects are expected to impact hydrodynamics only for \(d_p/d_L < 20\).[67] The \(d_p/d_L > 20\) for the activated carbon in this study ensured that wall effects (or the impact of vessel diameter) were not expected to occur, which is supported by the experimental results.

**DISCUSSION**

**Factors influencing project success**

Summer internships last approximately three months. This is a limited amount of time for an individual to conduct a research project, particularly one with an experimental component. The primary factor leading to the success of the project was the background knowledge and lab experience the student already had from his thesis research. Another factor that made the project successful was use of safe chemicals at low temperature and pressure; this expedites the MOC (safety review) process. Additionally, a thorough review of the internal resources allowed the student to ask the right questions and develop a correct procedure. Lastly, use of non-proprietary material to study a fundamental issue allowed for ease of publishing with respect to intellectual property. In the case where a more complicated system were to be used, it is recommended that the experimental setup be manufactured and approved prior to arrival of the student. One improvement that could be made to the internship process would be to provide the student with copies of proprietary company reports and other documents describing relevant past work prior to the project start.

**Benefits to industry, academia, and the student**

The results attained demonstrate the significant benefits of aligning an internship with the student’s thesis. The company directly benefits by having an individual with the correct expertise solve a relevant problem. The student benefits by adding to his or her thesis work and gaining a well-grounded understanding of the practical motivation for his/her research. This is in contrast to the alternative where the internship is focused on a different topic. In the latter case, the gains made by both the company and the student will be less. Furthermore, the time spent away would not be in support of the student’s thesis, effectively delaying completion of the degree. Rather, internships that are related to a student’s thesis should be pursued whenever possible, and are most likely to originate from existing collaborations or relationships of the academic advisor with industry.

Alongside the benefits to a student’s thesis that occur in this case, the student is also able to learn new procedures and practice his or her networking, teamwork, presentation, and project management skills as well as gain an understanding of work culture in industry. Additionally, the contacts made enhance the existing collaboration and bring opportunities for the student’s academic advisor and school. A further benefit of this work is that it shows the complexities that arise in real problems; this demonstrates the continued need for lecturers to stay well-informed of their respective fields and connect basic fundamentals to actual practice. From the perspective of the company, a relevant problem is solved, recruiting is improved at the school, and research directions may be provided to the school that lead to a greater number of graduate students with a background relevant to industry.

**CONCLUSION**

An experimentally based project was completed as part of an internship at Dow. This work included review of internal literature, design, setup, safety review, running experiments, analysis, and reporting of the results. The data showed that, by using a thorough pre-wetting procedure, vessel diameter did not have a significant effect on the hydrodynamics, which confirms the lack of wall effects expected for high values of \(d_p/d_L\). The primary factor in the success of this work was that the project was within the scope of the graduate student’s thesis. As such, he was able to apply the knowledge he already had regarding trickle bed hydrodynamics to solve a problem of industrial importance. The learning that resulted for industry and academia included the technical result itself and associated methods, while the student also learned about the work and safety culture in industry. More broadly, the stronger ties resulting from the collaboration may have a role in enhancing education at the school.

**ACKNOWLEDGMENTS**

The authors acknowledge The Dow Chemical Company for providing funding for this work. The authors also thank Billy Smith for his assistance on this project.

**NOMENCLATURE**

\(d_p\) particle diameter, m
\(d_L\) reactor column diameter, m
\(L\) bed length, m
\(g\) gravimetric constant, m/s²
\(v_L\) liquid superficial velocity, mm/s
\(v_G\) gas superficial velocity, mm/s
\(\Delta P\) pressure drop, Pa
\( \rho_L \) liquid density, \( \text{kg/m}^3 \)

\( \eta_L \) dimensionless pressure drop (\( \eta_L = -\frac{\Delta P}{\rho_L Lg} + 1 \))

REFERENCES

METHOCEL™ is a water-soluble polymer derived from cellulose with a variety of applications in many industries. A well-established product for The Dow Chemical Company (“Dow”), METHOCEL has been produced for more than 75 years and is used in manufacturing of food and pharmaceuticals, among many other areas. Production of the versatile polymers occurs at Dow locations in North America and Europe.

The polymeric backbone of cellulose reacts with reagents such as methyl chloride (MeCl) and propylene oxide (PO) to form METHOCEL variants with a vast range of properties. For example, viscosity levels can range from 3 to 200,000 mPa·s. The properties of the materials are adjusted based on the side chain properties of the cellulose polymer. Methyl cellulose is formed when MeCl reacts with the hydroxyl groups on a given glucose unit. Three hydroxypropyl groups are available per glucose, and the degree of substitution (DS) for a METHOCEL product is defined as the average number of hydroxyl groups that react with MeCl per glucose molecule.

The reaction of hydroxyl groups with PO can provide even more variety to the cellulose polymers, forming five other categories of Dow products and a plethora of specific recipes. The extent to which cellulose reacts with PO is described by the molar substitution (MS), or the number of moles of hydroxypropyl groups per mole of anhydroglucose in the chain.
While the reaction of MeCl with a hydroxyl group effectively caps the side chain, preventing further reactions, multiple reactions with PO can occur on the same side chain. Figure 1 shows the types of METHOCEL products and the sites for reaction.

Producing METHOCEL with the desired DS and MS is heavily dependent on the feed rates, reaction time, and temperature profile of a reactor system. As a well-established process in Dow, working METHOCEL recipes exist that meet consumer requirements. However, there is recognized potential for process and product optimization in this area utilizing modeling techniques in established software such as Aspen Custom Modeler® (ACM). A model with accessible data input through Microsoft Excel® that accurately predicts DS and MS (molar substitution) would provide ample opportunity to improve product properties, reduce cycle time, optimize feed inputs, improve process economics, and safely test new METHOCEL recipes. The scope of this internship project begins with the conversion of existing kinetic models into ACM. After integrating this model with Microsoft Excel, kinetics and heat transfer predictions will be validated with plant data and the potential for optimization is demonstrated with a specific METHOCEL recipe.

The internship was presented to the student as an opportunity to incorporate a variety of chemical engineering concepts into one centralized project. Reaction kinetics, dynamic simulation, control principles, optimization, economic analysis, and statistics would all be required to properly implement and analyze a METHOCEL production model. Beyond this, a high level of comfort with a variety of chemical engineering software types would be necessary; the student had never used Aspen Custom Modeler before the internship, and the student was required to quickly adapt to the software. Exposure to controls simulation software, reactor modeling with POLYMATH, and Aspen Plus at Michigan State University (MSU) prepared the student for a smooth, swift adjustment to the new software tools available at Dow.

ASPERN CUSTOM MODELER AND MICROSOFT EXCEL INTEGRATION

Aspen Custom Modeler is a valuable modeling tool in the AspenTech suite of process simulation software. With the ability to execute dynamic simulations using equation-oriented modeling, ACM provided the platform for simulating a METHOCEL batch reactor. Kinetic data from Dow internal research was previously placed into ACM, and the program was designed such that a temperature profile and two feed stages for five reagents were available for user input. Initially, a user-programmed control scheme was also implemented.

During the project, the ACM model functionality was expanded to allow the input of four feed stages, a variety of cellulose loads and reactor properties such as volume, heat transfer coefficients, cooling water rates, etc. The final ACM flowsheet for the METHOCEL model is shown in Figure 2. Five feed streams, each representing one major feedstock component, enter the batch reactor. The times and flow rates of the feeds, provided by the user, are used to switch the streams on and off. The previously programmed control scheme was updated with a built-in ACM PID controller to simulate temperature control around the desired profile.

To make the model more accessible for those who are not familiar with ACM, a user interface was developed in Microsoft Excel to execute the model. Thus, a user can input data in a familiar environment, and execute the model with instantaneous feedback involving temperature, pressure, and product DS/MS. Upon completion of the simulation, all relevant data are also automatically extracted into the spreadsheet.

Figure 1. Chemical structures of methylcellulose and hydroxypropyl methylcellulose.
to provide plots of reactor performance. Excel VBA Macros were utilized to input the data, execute the desired ACM model, and retrieve results. The basics for linking ACM with Microsoft Excel are found in AspenTech’s user guides for ACM. A screenshot of this Microsoft Excel interface is shown in Figure 3.

The linking of the Microsoft Excel spreadsheet with ACM was a unique part of the internship and added immense utility to the tool but would not have been possible for the student in a three-month internship without a variety of factors. First, the student had been able to take computer science courses outside of his major at MSU, developing a skillset that is becoming increasingly useful and important for chemical engineers, especially those with interest in computational research. Such skills are often undervalued or underdeveloped inside the chemical engineering major. Beyond this, the student had access to multiple subject matter experts inside of Dow who had utilized similar VBA functionalities and who were well-acquainted with the Aspen suite of software. By the end of the internship, the student was even included in monthly seminars inside of Dow for those working with Aspen on a regular basis, a unique opportunity that many undergraduates will never receive.

![Figure 2. ACM flowsheet of METHOCEL batch reactor.](image)

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<thead>
<tr>
<th>Feed Basis</th>
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![Figure 3. Microsoft Excel user interface for ACM-based METHOCEL model (user enters desired values to replace “x” entries).](image)
MASS BALANCE

For the mass balance, the ordinary differential equation for the change in moles of each component due to reactions and the inlet streams was calculated as follows, assuming a well-mixed reactor with no concentration gradients:

\[
\frac{dM(i)}{dt} = \sum_j \frac{F_{in,j}}{MW_j} X_{n,j,i} + V_{L} \sum_j V_{1,j} r_{j}
\]

\( \frac{dM(i)}{dt} = \) change per time in moles component \( i \), kmol/s

\( F_{in,j} = \) mass flow into the reactor of stream \( j \), kg/s

\( MW_j = \) molecular weight of stream \( j \), kg/kmol

\( X_{n,j,i} = \) liquid mole fraction of component \( i \) in feed stream \( j \)

\( V_{1,j} = \) stoichiometric coefficient of component \( i \) in reaction \( j \)

\( V_{L} = \) liquid volume calculated from total moles and density, m\(^3\)

\( r_j = \) reaction rate, kmol/m\(^3\)/s

Below is a sample rate expression:

\[
r_i = r_{emp,i} k c_i^\alpha
\]

\( r_{emp,i} = \) empirical reaction rate function, kmol/m\(^3\)/s

\( k = \) reaction rate constant

\( c_i = \) concentration of component \( i \) in the liquid volume, kmol/m\(^3\)

\( \alpha = \) reaction component order

KINETIC MODELING

The final METHOCEL™ model constructed in ACM contained more than 30 possible reactions. The kinetics of each reaction were implemented utilizing an Arrhenius equation approach following Eq. (3).

\[
k = A e^{\frac{E_a}{RT}}
\]

Values for the pre-exponential factor \( A \), and activation energy \( E_a \) were calculated experimentally through previous analysis of a pilot plant METHOCEL process. Utilizing the known stoichiometries of METHOCEL reactions and the reaction rates provided from Eq. (3), the kinetics were fully implemented in the model for the plant reactor.

Multiple recipes of METHOCEL from three different product brands were used to validate the empirical kinetic model. Plant data were extracted from the Midland, MI, plant, including the temperature profile of the reactor, the initial loads and feed stages of reactants, and general reactor characteristics. Using this plant data, predictions of the DS and MS for each batch were calculated in ACM and exported into Microsoft Excel.

The results immediately indicated that the DS is accurately predicted within a reasonable percent error for each METHOCEL product and recipe tested. Thus, the kinetic parameters used for reactions involving MeCl reacting with cellulose did not require any updating from the previous batch trial data. However, the results from the plant validations required improvement in batches that required MS predictions, indicating an invalid kinetic parameter for a PO reaction.

Plotting the values of predicted MS from the model and calculated MS from analytical chemistry should theoretically yield a profile falling on \( y=x \). An example of such a plot is demonstrated in Figure 4, with hypothetical data representing how batch validation trials could appear. In reality, unlike in Figure 4, a systematic under-estimation of MS for PO-based METHOCEL recipes was discovered based on the plant trials. By reviewing the reactions included in the model, a specific pre-exponential factor for a PO reaction with cellulose was identified that had a key influence on the predicted MS of the product with minimal impact on the final DS values.
A sensitivity analysis was conducted on the value of the pre-exponential factor to identify if changing this value could universally improve the accuracy of the model for all batches that involve PO reactions. The goal of the sensitivity analysis is to minimize the total residuals from the predicted and calculated MS values so that the model can be utilized across all METHOCEL product types and recipes. The analysis initially analyzed 25 different plant batches from five different recipes and three product types in order to find an ideal value of the pre-exponential factor. After this initial analysis, the new pre-exponential factor was tested again with 25 new batch trials. The sensitivity analysis yielded an improved kinetic model that predicted MS and DS within an acceptable percent error range across all recipes.

HEAT TRANSFER MODEL

In the model, the energy balance (shown as a conceptual diagram in Figure 5) is calculated as follows:

\[ dU_\text{tot} = \sum F_{i,j} + Q_i + Q + Q_j \]  

\[ dU_\text{tot} = \text{change in total energy in the system, kW} \]
\[ F_{i,j} = \text{mass flow into the reactor, kg/s} \]
\[ H_{i,j} = \text{specific enthalpy of feed stream, J/kg} \]
\[ Q_i = \text{heat released by all reactions, kW} \]
\[ Q = \text{heat transfer, kW} \]
\[ Q_j = \text{heat added by agitator shaft work, kW} \]

The reaction heat is calculated as follows, assuming a well-mixed reactor with no temperature gradient in the reaction mixture:

\[ Q_i = V_{liq} \sum \Delta H_{i,j} r_j \]  

\[ \Delta H_{i,j} = \text{heat of reaction, J/mol} \]
\[ r_j = \text{reaction rate, mol/m}^3/\text{s} \]
\[ V_{liq} = \text{liquid volume calculated from total moles and density, m}^3 \]

The reactor is heated or cooled via the reactor jacket and cooled via a heat exchanger:

\[ Q = Q_{\text{jacket}} + Q_{\text{cond}} \]  

\[ Q_{\text{jacket}} = \text{heat transfer from jacket, kW} \]
\[ Q_{\text{cond}} = \text{heat loss from heat exchanger, kW} \]

The energy removed via the jacket is calculated using the following relationship:

\[ Q_{\text{jacket}} = k_j A_{\text{jacket}} (T_{\text{jacket}} - T_{\text{out}}) \]  

\[ k_j = \text{heat transfer coefficient of liquid to jacket, kW/m}^2/\text{K} \]
\[ A_{\text{jacket}} = \text{jacket area, m}^2 \]
\[ T_{\text{jacket}} = \text{temperature of jacket, °C} \]
\[ T_{\text{out}} = \text{temperature inside the reactor, °C} \]

The energy accumulated in the jacket is the difference between the energy removed from the jacket by heat transfer to the cooling water and the energy transferred from the reactor:

\[ c_{p,\text{jacket}} m_{\text{jacket}} \Delta T_{\text{jacket}} = k_{\text{env}} A_{\text{jacket}} (T_{\text{env}} - T_{\text{jacket}}) - Q_{\text{jacket}} \]

\[ c_{p,\text{jacket}} = \text{heat capacity of jacket, J/kg/K} \]
\[ m_{\text{jacket}} = \text{mass of jacket, kg} \]
\[ k_{\text{env}} = \text{heat transfer coefficient of jacket, kW/m}^2/\text{K} \]
\[ T_{\text{env}} = \text{jacket controller temperature, °C} \]

The energy that is transferred from the jacket equals the energy change in the cooling water:

\[ k_{\text{env}} A_{\text{jacket}} (T_{\text{jacket}} - T_{\text{env}}) = F_{\text{jacket}} c_{p,\text{water}} (T_{\text{inlet}} - T_{\text{outlet}}) \]

\[ T_{\text{inlet}} = \text{jacket cooling inlet water temperature, °C} \]
\[ c_{p,\text{water}} = \text{cooling water heat capacity, J/kg/K} \]

The heats of reaction for the METHOCEL recipes were implemented from previous experimental data, and were used to calculate the adiabatic temperature rise in the reactor along with the amount of cooling water necessary. The dynamic nature of the batch reactor and control scheme prevented the use of a basic log-mean temperature difference expression of heat transfer to a jacket. Thus, the heat transfer was modeled using a heat transfer balance on the reactor wall and cooling water jacket. This required the approximation of either film heat transfer coefficients and thermal conductivities or an overall heat transfer coefficient. This choice was presented to the user in the Excel interface. Implementation of the heat transfer model enabled reasonable matching to plant data.

Figure 5. Heat transfer model taking into account all inlet and outlet streams (including steam and cooling water), heat losses to the environment, phase changes, the agitator’s dissipated energy, and temperature changes in the reactor mass.
STUDENT INTERACTIONS FOR MODEL VALIDATION

The implementation and validation of the METHOCEL model required close collaboration with a variety of subject matter experts within Dow. Multiple perspectives were required due to the number of production locations and the variety of METHOCEL products. To ensure the student was meeting expectations regarding model development, biweekly conference calls were scheduled with representatives from North American and European plants. The student was able to summarize results and gain feedback on the model developments, demonstrating the clear need for written and verbal communication skills to be developed during undergraduate education. This was reiterated during his two internal Dow seminars to subject matter experts in the METHOCEL community and in the Reaction Engineering group of Core R&D.

As the model was directly validated with data in Midland, MI, the student interacted directly with a plant operator as well as a METHOCEL engineer to acquire the data and understand the systems in place in Midland. In particular, these interactions gave valuable insights into why the model deviated at times from plant operation, specifically in terms of the heat transfer expectations. As some curriculums move away from requiring a course on control principles for chemical engineers, these concepts were crucial for the student’s understanding of the control scheme for the METHOCEL reactor and for choosing the control scheme in ACM.

The validation of the model highlights the importance of process simulation instruction in chemical engineering education. The model simply could not be constructed without tools such as Aspen or Microsoft Excel, and the student’s experience with this software was crucial for the overall internship. Importantly, instruction should be careful to emphasize what is really occurring beneath the user interface for chemical engineering software; if Aspen or similar software is presented as simply a black box simulation, students will be lacking in their ability to troubleshoot real models or solve problems effectively with these tools. For this particular internship, without a fundamental understanding of reaction kinetics, heat transfer, and control systems, the student would not have been able to accurately represent the METHOCEL process.

His background with computer science and with Aspen was extremely helpful, but the chemical engineering principles should remain at the center of effective modeling instruction.

BATCH OPTIMIZATION CASE STUDY

The true utility of the METHOCEL ACM model exists in the potential to optimize the cycle times and product yields of the METHOCEL process. This was demonstrated with a case study involving a specific METHOCEL product recipe. The specific recipe tested required a two-stage feeding process, with two separate temperature ramps during the process and a considerable time of cooling between each stage. The process had not previously been optimized before the creation of the ACM model and Excel interface.

Many possible parameters could be considered for an objective function in the optimization of a METHOCEL recipe, including the reduction of cycle time or the maximization of product yield. Beyond this, many factors can be considered during the optimization, ranging from the temperature profile to product feed rates. For this specific case study, the temperature profile of the recipe was analyzed to minimize the cycle time of the reactor. The optimization was constrained with the required values of molar substitution and degree of substitution, to ensure that product characteristics would not change. The cooling water and heats of reaction for the process were also key factors in determining feasibility of new recipes.

A generic temperature profile for the recipe was constructed by averaging the temperature profiles for multiple batch trials from the Midland plant. This profile was used as a base case for the optimization process, and initial values of the DS and MS were then calculated as a comparison for all further runs. The ACM model was then utilized to test profiles with shorter cooling times in between stages, along with faster temperature ramping in the stages.

Optimization of the process demonstrated that the cycle time of a batch could be reduced considerably simply by changing the temperature profile sent to the controller of the reactor, with minimal change in the final DS and MS of the product. The results also demonstrated that this cycle time reduction could be tested in a sequence of steps in the plant; that is, acceptable temperature profiles that would eliminate 10 minutes, 20 minutes, etc., were provided. This would allow plant trials to occur in such a way as to ensure product quality was not hampered by changes in temperature profile. If the fully optimized recipe is realized in plant operation, the optimization would noticeably improve the net present value of the METHOCEL process.

The optimization case study performed during this evaluation was a very simple, “hand-optimization” case in which the user of the model made intuitive changes in the temperature profile that would lead to a reduction of cycle time. The Excel interface and ACM model provide opportunities for such optimization across all METHOCEL recipes and batch types. However, a more robust and impactful optimization process could be conducted if a similar model was developed in software such as GAMS. Future work in this area should certainly involve investigation of this potential.

CONCLUSIONS

This summer internship project at Dow provided useful experience in equation-oriented modeling while demonstrating the technical feasibility and benefits of simulating plant processes. The investigation required knowledge from a variety of core
chemical engineering principles, involving reaction kinetics, transport, and process control. METHOCEL production was accurately modeled using Aspen Custom Modeler and linked with Microsoft Excel to provide users with the ability to easily input run specifications. Empirically derived kinetics and heat transfer models were validated using real plant data within reasonable levels of accuracy. The utility of the model was then demonstrated through batch optimization trials, demonstrating clear value from plant economics analysis. The work resulted in two internal seminars and an internal publication for the student.

ACKNOWLEDGMENTS

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REFERENCES


2. Proprietary Dow report describing gPROMS model
HEAT EXCHANGER LAB
FOR CHEMICAL ENGINEERING
UNDERGRADUATES

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Chemical Engineering Laboratory is a required course in the undergraduate chemical engineering curriculum at The University of Akron to give students hands-on experience with the fundamental chemical engineering concepts of transport phenomena, thermodynamics, and reaction kinetics, while also designing experiments, collecting/analyzing data, and presenting their results. This course is taken in the sixth academic semester, with Mass Transfer Operations as a prerequisite and taken concurrent with Chemical Reaction Engineering and Fluid & Thermal Operations as corequisites. The heat exchanger laboratory described in this paper is one of several laboratory experiences of the 15-week course. Since students do not get extensive experience with the application of scale-up principles outside of a few discussions in the lecture courses, this heat exchanger lab was seen as an opportunity to teach the students how to apply scale-up concepts.

Proper scale-up applies the principles of geometric and dynamic similarity to obtain accurate prediction of the tank performance between the two tank sizes. Geometric similarity requires ratios of characteristic length in the tank geometry, such as impeller diameter to tank diameter or liquid depth to tank diameter, to be the same for the small- and large-scale tanks. Dynamic similarity requires the ratios of forces and ratios of energies, defined by dimensionless groups such as Reynolds number and Prandtl number, to be the same between the small and large tanks.¹ [2,3]

The heat exchanger laboratory had two parts (described in detail in later sections). In Part 1 the students observed and compared performances of two geometrically similar but different size stirred tanks having very simple internal coil heat exchangers. They applied energy balances to evaluate and compare the performances and to deduce the scale factor for predicting tank performance. This comparison of the operation of two different scale tanks reinforced the concepts of scale-up and gave the students confidence in scale-up application.

In Part 2, the students designed and fabricated their own heat exchange coils and tested them in a small 10 gallon tank. The students were permitted to use baffles, extended surfaces, or
different tube lengths and diameters compared to the simple
design used in Part 1. The students applied scale-up principles
to predict performance of a larger scaled-up tank using their
coil design. Due to resource limitations the students did not
physically test their designs on a larger tank but they supported
their design predictions through the principles of scale-up in
their oral presentations.

The learning objectives of the laboratory experience in­
cluded:

• Hands-on experience with cutting, bending, and con­
necting tubes.
• Hands-on experience in attaching and using fittings,
valves, flow meters, thermocouples, and stirrers.
• Interpretation of experimental results and sources of
experimental errors to link what they learned in class­
rooms about fluid flow and heat exchange to a practical
application.
• Application of engineering concepts to an unsteady state
process.
• Application of concepts of scale-up and dimensional
analysis.
• Design of a workable solution to a problem with mul­
tiple constraints.

Specific laboratory activities and tasks included:

• Preparation of technical drawings.
• Use of tools to fabricate the internal heat exchange coil.
• Preparation of an experimental plan and lab report.
• Analysis of the experimental data.
• Oral presentation of the experimental results and predic­
tion of scale-up performance of a large tank based on
the student-designed heat exchanger coil.

The laboratory course was 15 weeks long. The students
were divided into Monday/Wednesday groups and Tuesday/
Thursday groups. The groups met for three hours on each of
their assigned group days for six hours of laboratory time
each week. All of the students attended a common one-hour
lecture period on Wednesdays that covered a range of
topics pertinent to the course and developmental
topics for the chemical engineering degree. In the first week of
the course the laboratory periods were used for safety instruc­
tions and administrative functions. In the last two weeks of
the course the laboratory periods were used to complete lab
activities, make up for unfinished lab activities, and complete
administrative activities.

The heat exchange experiment was one of four laboratory
activities conducted during weeks 2 through 13 of the course.
The four laboratory activities each lasted three weeks with
one-fourth of the students rotating through each activity every
three weeks. In the most recent offering of the course (Spring
semester 2015) the students were organized into four teams of
three students each in each rotation. The three-person teams
were an ideal size because there were enough students to ef­
tensively conduct the experiments and all students contributed
to the team activities.

COMPARISON OF HEAT EXCHANGE PERFOR­
MANCE OF TWO SCALED STIRRED TANKS

Heat exchange performance was compared between a
10 gallon stirred tank and a 50 gallon stirred tank. The
two tanks are shown in Figure 1. A closer view of the 10
gallon tank is shown in Figure 2. Both tanks were geo­
metrically similar and were equipped with geometrically
similar simple copper tube coils through which cold water
flowed. The tanks were equipped with air-pressure driven
globally similar propellers to agitate the tank water
and with rotameters to measure the cooling water flow rate
through the heat exchange coils. Hand-held thermocouples
were provided to measure water temperatures over time. A
digital strobe light was used to measure the rotation rate of
the impeller. The impeller rotation rate was controlled via
an air pressure regulator valve.

The scale factor, S, between the two tanks is defined as the
ratio of the tank diameters and had a value of 1.64. The 3 inch
and 5 inch diameter three-blade propellers used in the small
and medium tanks, respectively, had nearly the same scale factor (1.67). Internal cooling coils were fabricated of 1/4 inch and 3/8 inch copper tubes with scaled geometries (tube length, same number of tube coil turns, scaled coil diameter, and located at the same scaled positions in the tanks). The ratio of the outside diameters of the copper tubes of 1.50 was not the same as 1.64 but close enough for the demonstration.

The demonstration started with the tanks filled with hot water (approximately 50 °C) to a depth equal to the respective tank diameters. Cooling water flowed through the coil at scaled flow rates for the two tanks to give scaled performance. The tanks cooled in about 20 and 40 minutes respectively to within a few degrees of the cooling water inlet temperature. The students plotted and evaluated the temperature–time data to determine the characteristic performance constant, c

\[ c = \frac{m}{M} \left[ 1 - \exp \left( \frac{-U A}{mC_s} \right) \right] \]  

in the performance equation (see Appendix for derivation)

\[ -\ln \left( \frac{T - T_o}{T_i - T_o} \right) = ct \]  

where \( T \) is the tank temperature at time \( t \), \( T_o \) is the cooling water inlet temperature (constant), and \( T_i \) is the initial tank temperature.

Theoretically, it can be shown that if the geometric properties (tank diameter, tube diameter, and impeller diameter) all scale by \( S \), such that \( d_{\text{large}} = d_{\text{small}} \cdot S \), then the performance constants scale by \( S^2 \),

\[ \frac{c_{\text{small}}}{c_{\text{large}}} = S^2 \]  

The students collected the experimental data, plotted the results, and calculated the ratio \( \frac{c_{\text{small}}}{c_{\text{large}}} \). They discussed factors that contributed to error in the measurements. In situations when the ratio \( \frac{c_{\text{small}}}{c_{\text{large}}} \) significantly deviated from \( S^2 \) the students further discussed how they would improve the experiments to ensure operating conditions were consistent with model constraints.

The comparison helped prepare the students for running and evaluating their own experiments by introducing them to the instruments and to the tasks they need to do during the experiments. For their own experiments the students were required to change the coil design shape and dimensions. The students were allowed to use fins, extend surfaces, and add baffles. In all cases the student teams kept the designs simple due to the limited time available for fabrication.

**STUDENT-DESIGNED INTERNAL HEAT EXCHANGE COILS**

The students were given the following scenario:

*The heat exchanger design team is part of an engineering consulting company. A client of the consulting company wants to retrofit a stirred tank bioreactor with a heat exchanger to cool the tank contents from 70 °C to less than 25 °C. The tanks contain 25 m³ of aqueous liquid. Cooling water at 15 °C is available on-site but with a constrained maximum flow rate of 10 liters per minute for accomplishing the heat exchange.*

The teams used this information to propose a design and run small-scale tests to predict the time needed to cool the contents of the bioreactor. The results of the experiments and the predicted cooling time were presented to the customer with a scaled-up design, performance prediction, and cost estimate.

For the experiments the students were provided a 10 gallon tank equipped with a 3 inch propeller stirrer for the small scale testing, as shown in Figure 2. Hot tap water at about 50 °C was used as the tank fluid, and cold tap water at about 5 °C to 15 °C was used as the cooling water. Brass union connections were used at the top of the tank for attachment of the students’ heat exchangers. The teams were allowed to choose either 0.25” or 0.375” outside diameter copper tubing for fabrication of their coils. The coil design (size of coil turning radius, number of coils, shape of coil, etc.) dictated the total coil length. Based on prior experience, the students were encouraged to keep the total tube lengths less than 4 m, otherwise the cooling water temperature approached the tank water temperature and the extra tubing was ineffective in the heat exchange. With the above information, the students made a technical drawing of their heat exchanger coil design that was reviewed by the teaching assistant and a technician prior to construction of the coil. In their reviews, the teaching assistant and technician offered suggestions to improve or simplify the construction effort of the designs proposed by the students.

Once the design was approved by the teaching assistant and the technician, the students were given fittings and copper tubing. Fabrication was done in a machine shop with tools available for cutting and bending the tubing. Sometimes the bends in the coil were large and students found objects of appropriate diameter around which they could bend the tubes. A technician was available to assist if needed and to teach the students proper and safe use of the tools. Machining (lathe, mill, etc.) was available but seldom needed.

*Figure 3. A typical student-designed and fabricated 1/4 inch copper tube coil.*
Teams were allowed to interact and observe each other during fabrication of the coils. A typical student coil is shown in Figure 3.

**Experimental plan**

Before running the experiments, the teams prepared experimental plans that described the procedures to follow, measurements to be recorded, and a description of how the data would be evaluated. The plan was reviewed by the teaching assistant prior to running any experiments, to ensure plans could be run safely and to check for any items the teams may have overlooked.

The students used the given parameters of the hypothetical large scale tank to scale down the operating conditions at which the small scale tanks were run. A constraint was placed on the large tank that the maximum cooling water flow rate available was 10 liters per minute. This constraint forced the students to scale the flow rate of the cooling water for the small tank based on constant Reynolds number between the scales. Since water was used as the tank fluid and the cooling fluid at both scales the fluid properties were assumed to be the same in the scale-up calculations used to determine the appropriate flow rates and impeller rotation rates for the experiments.

Since the scale factor, S, between the small and large tanks was defined as the ratio between the tank diameters, and the fluid height in the tank was equal to the diameter, the students determined S to be $S = \left( \frac{d_{	ext{large}}}{d_{	ext{small}}} \right)^{1/3}$ = 8.91. To find the flow rate inside the tube, the Reynolds number for flow was held constant ($Re_{\text{large}} = Re_{\text{small}}$) where inside of the tube, $Re = \frac{\rho v d}{\mu} = \frac{4Q}{\pi d^2 \mu}$, hence the flow rates were related as $Q_{\text{large}} = S^2 Q_{\text{small}}$. To find rotation rate, the tank agitation Reynolds number was held constant ($Re_{\text{stirr}} = Re_{\text{cyl}}$) for the stirrer, $Re = \frac{n d \rho}{\mu}$, hence the stirrer rates were related by $n_{\text{small}} = S^2 n_{\text{large}}$.

After fabricating their coils, the students attached their coils to the 10 gallon tank, checked for leaks, filled the tank with hot water, set the appropriate rotation rate with aid of the digital strobe light, set the appropriate cooling water flow rate with a rotameter, and recorded their temperature data over time. The thermal energy balance equations from transport phenomena provide a relation to determine the overall heat transfer coefficient, which can be scaled appropriately to make a prediction of the cooling time for a larger tank, as seen in the next section.

**EXPERIMENTAL RESULTS AND DISCUSSION**

The students recorded tank and cooling water temperatures over time. They plotted the dimensionless temperature versus time to determine the performance constant, $c$, as the slope of a linear fit of the data through the origin, as indicated by Eq. (2). An example plot is shown in Figure 4.

**Scale-up**

From $c_{\text{small}}$ for the small tank, and the scale factor $S$, the constant $c_{\text{large}}$ for the large tank was determined from Eq. (3). For the example data in Figure 4, $c_{\text{large}} = 3.25 \times 10^{-5}$. The cooling time for the large tank based on the experimental data in Figure 4 can be determined from Eq (2) to be $t_{\text{large}} = 551,000$ s = 6.4 days.

Typical coil designs by the teams had large tank cooling times ranging from 4 to 7 days. This may seem to be a long time. During the presentations the students were asked to discuss why it seemed to take so long to cool the large tanks (due to assumptions of negligible heat loss to surroundings, limited tube length, and limit on cooling water flow rate), what factors controlled the cooling (cooling water temperature and flow rate, and surface area for heat transfer), and what recommendations they would give the client to speed up the cooling time (increase cooling water flow rate, use a longer tube coil, and consider pumping the hot tank fluid through a shell and tube exchanger to another tank).

**Error analysis**

Several sources of error in the experiments were identified. Variations in temperature of the cooling water from the building supply, if significant, could affect the rate of cooling of the tank water. Multiple thermocouples were used, and sometimes the thermocouples gave slightly different readings. For designs that needed a lower rotation speed of the propeller, the motor sometimes had difficulty maintaining a steady rotation speed. Human error of improper or inconsistent data collection was
observed, particularly if different students took measurements in different experimental runs. Some of the students had difficulty using the digital strobe light to measure, adjust, and control the rotation rate of the propeller.

EDUCATIONAL ASSESSMENT

The evaluation of the students' effort in this laboratory section was done by grading of the student presentations. A list of the topics covered in the presentation and guideline for assigning points for the grades are listed in Table 1. The list was provided to the students at the start of the three-week lab session so they knew what was expected of them in the final presentations.

In the final presentation the students presented the topics in the roles of the Chief Executive Officer (CEO), Chief Technical Officer (CTO), and Chief Financial Officer (CFO) or Vice President of Marketing. Each student earned up to 30 total points based on their individual performance and up to 20 total points for the team or group score. Information was given to the students on the first day of the three-week lab session that indicated the expected content for each portion of the presentation. The students had prior instruction in economic analysis from a Process Economics course from the chemical engineering department in their fifth academic semester. The students also had prior marketing analysis experience from a Project Management and Teamwork class in their first, third, and fifth academic semesters where they work in a vertically integrated team consisting of students from all levels within the program where marketing is one of the required tasks. The other lab experiences in this course required the students to complete detailed written experimental reports, short executive summaries, and technical presentations. The economic and marketing analysis in the heat exchanger lab was used to give the students a more well-rounded experience from the course as a whole.

The lab instructor and teaching assistant played the roles of a potential customer during the team presentations and asked questions relevant to the expected content as well as questions to assess the students' knowledge of the fundamentals of heat transfer.

Most students initially struggled explaining the heat exchange performance of the stirred tank because the tank operated as an unsteady state process while the cooling water flowing through the copper tube performed as a quasi-steady state process (the time rate of change of the temperature of the cooling water was very small compared to the rate of temperature change along the length of the coil). This may be because most of the theoretical coursework the students have taken to this point focused on steady state processes. Some students struggled with the fundamentals of scale-up, and had only a shallow understanding of why the dimensionless groups, such as the Reynolds Number, are held constant between the small- and large-scale tanks.

| TABLE 1 |
| Example evaluation rubric for student presentations |

<table>
<thead>
<tr>
<th>Category</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEO</td>
<td>Executive summary (key points)</td>
</tr>
<tr>
<td></td>
<td>Business model</td>
</tr>
<tr>
<td></td>
<td>SWOT analysis (strengths, weaknesses, opportunities, threats)</td>
</tr>
<tr>
<td></td>
<td>Why is your design competitive? Primary competitors?</td>
</tr>
<tr>
<td>CTO</td>
<td>Tech overview</td>
</tr>
<tr>
<td></td>
<td>Performance of heat exchanger</td>
</tr>
<tr>
<td></td>
<td>Experiments (objectives, data collection, analysis of results)</td>
</tr>
<tr>
<td></td>
<td>Error analysis, difficulties</td>
</tr>
<tr>
<td></td>
<td>Justification of assumptions made</td>
</tr>
<tr>
<td>CFO/VP Marketing</td>
<td>Marketing plan</td>
</tr>
<tr>
<td></td>
<td>Economics of design and operations</td>
</tr>
<tr>
<td></td>
<td>Profit margin</td>
</tr>
<tr>
<td>INDIVIDUAL</td>
<td>5 pt. – Delivery/eye contact?</td>
</tr>
<tr>
<td></td>
<td>5 pt. – Knows material</td>
</tr>
<tr>
<td></td>
<td>5 pt. – Quality of slides/handouts</td>
</tr>
<tr>
<td></td>
<td>5 pt. – Content, accuracy, info appropriate</td>
</tr>
<tr>
<td></td>
<td>5 pt. – Q&amp;A, answers questions directly and professionally</td>
</tr>
<tr>
<td></td>
<td>5 pt. – Info relevant to audience?</td>
</tr>
<tr>
<td>TEAM</td>
<td>5 pt. – Presentation organization?</td>
</tr>
<tr>
<td></td>
<td>5 pt. – Team works as a team?</td>
</tr>
<tr>
<td></td>
<td>5 pt. – How well were presentation messages delivered?</td>
</tr>
<tr>
<td></td>
<td>5 pt. – Can team answer questions?</td>
</tr>
</tbody>
</table>

Students were asked how they felt about the lab experience and if they would recommend any changes. Feedback was positive; they felt the presentation format and technical discussions helped them understand how their coursework relates to a real-world problem, and they felt the hands-on experience to fabricate their own heat exchange coils was fun and valuable. They enjoyed the ability to run a simple experiment to demonstrate and apply the scale-up concepts. Some students would prefer more room for creativity with the exchanger design and the presentation. The students did not feel overwhelmed with the material they were asked to prepare for the final presentation and felt well prepared for economic and marketing discussion based on prior coursework.

RECOMMENDATIONS

The enthusiasm of the students to run this experiment combined with the simplicity of the experimental setup demonstrates the success of this laboratory experience. A number of variations could be incorporated into the laboratory exercise if time and resources permit. Alternative experiments could be run such as to compare and evaluate externally insulated versus non-insulated tanks, effects of stirrer geometry, and effects of fouling on the cooling coils. Students could explore variations in the heat exchange coil designs to optimize (minimize) the required cooling time. Systematic experiments could be run to explore the influences of single parameters such as length of the coil.
CONCLUSIONS

In conclusion, this laboratory experience was successful in teaching the students through a hands-on example of heat transfer and scale-up while being a simple enough experiment to run in three weeks of class time. The students successfully fabricated copper tube coils for cooling hot water in a stirred tank. The students applied principles of scale-up and analyzed data from a small tank to predict performance of a scaled large tank. The cooling of the stirred tank had multiple constraints and required students to design a workable solution taking into account the scale and the unsteady state performance of the stirred tank. The experimental results and prediction of performance of the large tank were reported in a presentation format. The student teams generally performed well. Student feedback on the laboratory exercise was positive.

ACKNOWLEDGMENTS

The authors would like to thank machine shop technician Frank Pelc for his technical assistance in setting up the experiment and helping the students build their heat exchangers.

REFERENCES


APPENDIX: DERIVATION OF EQ. 1

To derive Eq. (1), we start with the thermal energy balance from Transport Phenomena(5):

Energy Balance: \[ \frac{dU_{int}}{dt} = -\Delta(\tilde{m}\tilde{u}) + \dot{Q} + E_s + E_v \] (A1)

where \( \tilde{m} \) is the mass flow rate of the cooling water in the coil (a constant). The last two quantities on the right side are defined as \( E_s = \int V \frac{P(\nabla \cdot \nu)}{\rho} dV \) that accounts for the internal energy generation due to fluid compression, and \( E_v = \int V \frac{\nu \cdot \nabla \nu}{\rho} dV \) that is the generation due to viscous dissipation. The water is considered incompressible, constant density, hence from the mass continuity equation \( \nabla \cdot \nu = 0 \) and hence \( E_s = 0 \). The viscous dissipation is only important for high viscosity fluids or high shear rates; neither occur in the heat exchanger, hence \( E_v = 0 \).

The total internal energy is defined as

\[ U_{int} = \int \rho \tilde{u} dV \] (A2)

From thermodynamics

\[ \tilde{u} = C_v dT + \left( T \frac{dP}{dT} \right) _p dV \] (A3)

Assuming the fluid is incompressible, then \( dV = 0 \). Also from thermodynamics, \( C_p - C_v = T \left( \frac{dP}{dT} \right) _p \), for which the right side is zero (incompressible fluid), hence \( C_p = C_v \). Thus, we conclude

\[ \tilde{u} = C_v dT \] (A4)

By combining Eq. (A2) with (A3) and differentiating with respect to time the time rate of change of the total internal energy becomes

\[ \frac{dU_{int}}{dt} = \rho C_v V \frac{dT}{dt} \] (A5)

where the volume averaged temperature is defined as

\[ T = \frac{1}{V} \int V T dV. \]

Combining Eq. (A5) with (A1), and the total mass of fluid \( M = \rho V \), the energy balance becomes

\[ MC_p \frac{dT}{dt} = \tilde{m} \Delta (\tilde{u}) + \dot{Q} \] (A6)

**Energy balance on the coil:** The convection and heat conduction terms dominate in the coil. The time rate of change of the temperature of the fluid in the coil is small in comparison, hence the accumulation term in Eq.(A6) is neglected and the energy balance becomes

\[ \dot{Q}_{cool} = \tilde{m} C_v (T_{out} - T_{in}) \] (A7)

Integration of Eq. (A4) relates the convection term to the cooling water temperatures as

\[ \Delta(\tilde{u}) = C_p (T_{out} - T_{in}) \] (A8)

Hence, combining Eq. (A7) and (A8) with (A6) gives

\[ \dot{Q}_{cool} = \tilde{m} C_p (T_{out} - T_{in}) \] (A9)

**Energy balance on the tank:** The energy balance on the tank is obtained in a similar way. Convection in and out of the tank is zero and the heat conduction from the tank is equal but opposite in direction to the heat transfer from the coil, \( \dot{Q}_{tank} = -\dot{Q}_{cool} \), hence the energy balance reduces to

\[ MC_p \frac{dT}{dt} = -\dot{Q}_{cool} \] (A10)
Using the design equation to define the overall heat transfer coefficient

\[ Q_{\text{conv}} = U_o A_o \Delta T_i \]  

where

\[ \Delta T_i = \frac{T_{\text{in}} - T_{\text{a}}}{\ln \left( \frac{T_{\text{in}} - T_{\text{a}}}{T_{\text{in}} - T_{\text{a}}} \right)} \]

is the log-mean-temperature-difference, \( A_o = \pi d_o L \) is the outside tube area, and \( U_o \) is the overall heat transfer coefficient.

Combining Eq. (A9) and (A11) gives

\[ \frac{\text{mc}_p (T_{\text{in}} - T_{\text{a}})}{U_o A_o} = \frac{T_{\text{in}} - T_{\text{a}}}{\ln \left( \frac{T_{\text{in}} - T_{\text{a}}}{T_{\text{in}} - T_{\text{a}}} \right)} \]

which simplifies and rearranges to

\[ T_{\text{in}} = T - (T - T_{\text{a}}) \exp \left( \frac{-U_o A_o}{\text{mc}_p} \right) \]  

Combining Eq. (A13) with (A9) and (A10) and some rearrangement gives

\[ \frac{dT}{dt} = -\frac{\text{m}}{M} \left( 1 - \exp \left( \frac{-U_o A_o}{\text{mc}_p} \right) \right) (T - T_{\text{a}}) \]

The constant, \( c \), is defined as the lumped parameter

\[ c = \frac{\text{m}}{M} \left( 1 - \exp \left( \frac{-U_o A_o}{\text{mc}_p} \right) \right) \]

Eq. (A14) becomes

\[ \frac{dT}{dt} = -c(T - T_{\text{a}}) \]

which integrates to obtain the performance equation

\[ -\ln \left( \frac{T - T_{\text{a}}}{T_{\text{in}} - T_{\text{a}}} \right) = ct. \]
Undergraduate Laboratory Experiment
FACILITATING ACTIVE LEARNING OF CONCEPTS IN TRANSPORT PHENOMENA:
EXPERIMENT WITH A SUBLIMING SOLID

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Chemical engineering education is widely considered to have undergone a paradigm shift around the 1960s with the incorporation of transport phenomena in the curriculum.\[1\] The publication of the text *Transport Phenomena* by Bird, Stewart, and Lightfoot helped popularize the unifying treatment of momentum, energy, and mass transport based on microscopic or molecular description of processes. Whether inclusion of such treatment is warranted at the undergraduate level was debated vigorously in the subsequent decade or so,\[2\] and despite occasional objections, a course (or sequence of courses) in transport phenomena is firmly entrenched in most undergraduate chemical engineering curricula.\[3\]

The junior year of the undergraduate chemical engineering program at the University of Idaho features a two-semester-long sequence of mandatory courses entitled Transport and Rate Processes I and II. The text *Fundamentals of Momentum, Heat, and Mass Transfer* by Welty, et al.\[4\] has been used for both courses for a long time by various instructors teaching the courses. Both Transport and Rate Processes I and II are four-credit courses with lecture and laboratory components, and may or may not be taught by the same individual. In a case where two different instructors are used for the course sequence, the syllabi are coordinated to prevent any overlap of topics.

Students typically perform three experiments each semester, with two experiments each related to the three types of transport phenomena. Prior to this author assuming the responsibility for the transport courses, the experiments included viscosity determination, drag coefficient determination using a wind tunnel, thermal conductivity determination, diffusivity determination for a volatile compound using Arnold cell, and two gedankenexperiments.

Students typically find mass transport to be the most difficult of the three transport phenomena, possibly due to exposure to concepts in fluid flow and heat transfer in earlier Fluid Mechanics and Engineering Thermodynamics/Heat Transfer courses. However, the thought experiments and analysis assignments therein were not particularly useful in helping the students understand the mass transport concepts. The experiment described below was introduced out of the need to develop a laboratory exercise that would reinforce the mass transport concepts, be easy to understand and conduct, and ultimately, maintain student interest in a complex, mathematics-intensive subject.

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LABORATORY DESCRIPTION

Theory and objectives

Students in Transport and Rate Processes II are concurrently enrolled in the Separation Processes course. As a result, they may already be exposed to the design of separation equipment wherein they use mass transfer coefficients, without truly understanding the theoretical basis, the significance, or the correlations used for obtaining those. The experiment devised was aimed at clarifying these concepts and impressing upon students the importance of the mass transfer coefficient while being in the realm of transport phenomena, not transitioning into a unit operations/separations experiment.

The experiment was based on using a solid that exerts substantial sublimation pressure at ambient conditions. The experiment is similar to and builds upon one that has been described previously by Rodriguez, et al.[1] Upon exposure to air, a subliming solid will lose its mass, and the mass flux can be determined by monitoring the mass or volume of the solid as a function of time. Both the diffusion coefficient of the component in air, and the solid-gas mass transfer coefficient can be obtained from the experimentally obtained mass- (or volume-) time data.

The governing equations for the two situations—sphere and cylindrical disc—are as follows:

1. A sphere of subliming solid A:

For mass transfer of A in stagnant air, the pseudo-steady state assumption leads to the following equation for evaluating the diffusion coefficient:

\[ \frac{R_g T \rho_A}{2P \ln(1-y_{As}) M_A} (R_r^2 - R_0^2) = D_A t \]  

The mass transfer coefficient is obtained by equating the rate of mass (or volume) change to the convective mass transfer

\[ k_c = -\frac{\rho_A R_g T}{2M_A P y_{As}} \frac{R_r^2 - R_0^2}{R_0} \]  

where,

\[ D_A = \text{diffusion coefficient of A} \]
\[ k_c = \text{mass transfer coefficient of A} \]
\[ M_A = \text{molar mass of A} \]
\[ P = \text{total pressure} \]
\[ R = \text{radius of the sphere} \]
\[ R_0 = \text{radius at time } t = 0 \]
\[ R_r = \text{radius at any time } t \]
\[ R_g = \text{gas constant} \]
\[ t = \text{time} \]
\[ T = \text{temperature} \]
\[ y_{As} = \text{mole fraction of A in air at the surface of the solid} \]
\[ \rho_A = \text{mass density of A} \]

2. Cylindrical disc of the subliming solid A:

Mass transfer from the two circular faces of the disc (neglecting the mass transfer from the cylindrical surface) is treated as a case of transient diffusion into a semi-infinite medium. The governing equation for this situation is[4]:

\[ \left( \frac{\Delta m}{4R^2 M_A P y_{As}} \right)^{1/2} = D_A \pi t \]  

Alternately, the governing equation can be expressed in terms of the thickness of the disc, as shown in Eq. (4).

\[ \frac{\rho_A (z - z_0) R_g T}{2M_A P y_{As}} = D_A \pi t \]

The mass transfer coefficient is obtaining by the mass balance as above:

\[ k_c = -\frac{\rho_A R_g T}{2M_A P y_{As}} \int dz \]

where,

\[ \Delta m = \text{change in mass of the disc from initial mass in time } t \]
\[ z = \text{thickness of the disc} \]
\[ z_0 = \text{initial thickness of the disc} \]
\[ z_r = \text{thickness of the disc at time } t \]

The mole fraction of A at surface, \( y_{As} \), is obtained from the saturation pressure of A, \( P_A^* \), at temperature T.

\[ y_{As} = \frac{P_A^*}{P} \]  

Experimental measurements of mass and physical dimensions of samples as a function of time are used in the above equations to obtain both the diffusion coefficient \( D_A \) and the mass transfer coefficient \( k_c \). (Details of the derivation of the above equations are shown in Appendix A).

Assignment statement

The laboratory assignment handed to the students is shown in Table 1. The salient features of the assignment are:

- A concise statement of objectives and expected outcomes. Students are required to not only determine the parameters experimentally, but also to compare their results with theoretical predictions.
- A group assignment, with students having the responsibility for designing the experiments.
- Clear delineation of submissions/deliverables from the students. The required components of the pre-lab and lab report are listed along with the maximum credits for each component.
- Submission of an individual summary statement, wherein the student relates the experiment to theoretical concepts covered in the lectures.
Each group consisted of three or four students, and the pre-lab and laboratory reports were evaluated as a collective submission. The experiments were conducted using mothballs made of naphthalene or discs of p-dichlorobenzene, available at any superstore. The pre-lab report was due one week after assigning the experiment. Groups with satisfactory pre-lab reports were allowed to conduct the experiment over the next week, and the laboratory reports as well as the summary statements were due one week after the completion of the experiment.

DATA ANALYSIS

Experimental setup

As no fixed setup was specified, the students designed their own apparatus. Approximately two-thirds of the groups chose to work with naphthalene balls, while the rest of the groups chose p-dichlorobenzene discs. Typically, these were exposed to air either by suspending by a thin wire from a stand or by supporting them on sharp, pointed objects. The students most often drilled a thin hole through the center of the sphere or disc and threaded a wire through this hole to suspend the object. Some groups did not drill a hole but fashioned a wire-loop around the sphere to suspend it. The pointed objects used to support the sphere or disc included push pins, nails, toothpicks, and straightened paper-clips. The other end of this pointed object was fixed in a variety of support material including wooden or foam block or even a Styrofoam cup. Students either measured the mass of the object using a balance, or the diameter/thickness using a Vernier caliper. Students were also creative in designing the flow environment for mass transfer coefficient determination. While many groups set up the apparatus in fume hoods, some groups designed their own flow channels using everyday objects such as a bucket or a shoe box. They cut out holes in sides and put in small fans for a better control of the experimental conditions. Some of the groups who used p-dichlorobenzene discs also sealed the cylindrical surface to restrict sublimation from the circular surfaces only. Yet another group constructed an aluminum foil cylinder the diameter of the disc, constructing essentially an “Arnold Cell” for the solid with the disc at the bottom of the cylinder. Figure 1 shows the schematic representation of these arrangements.

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tr>
<td>Determination of Diffusion Coefficient and Mass Transfer Coefficient</td>
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</table>

**What:** Experimentally determine the diffusivity of the constituent of moth ball/disc and its mass transfer coefficient in air, and compare it to the theoretically predicted value.

**Why:** Both diffusivity and mass transfer coefficients are important parameters in mass transfer operations.

**How:** By designing the appropriate apparatus and making measurements.

<table>
<thead>
<tr>
<th>Pre-Lab Report (15 points)</th>
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<tbody>
<tr>
<td>1. Define the objective of the experiment (2 points)</td>
</tr>
<tr>
<td>2. Present the theoretical principle, and identify the parameters that need to be measured (4 points)</td>
</tr>
<tr>
<td>3. Describe the apparatus that will be used (2 points)</td>
</tr>
<tr>
<td>4. Describe the procedure (5 points)</td>
</tr>
<tr>
<td>5. List any possible hazards, precaution/safety measures to be taken, and post-experimental cleanup (2 points)</td>
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<table>
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<tr>
<th>Lab Report (30 Points)</th>
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<tbody>
<tr>
<td>1. Describe the actual procedure used (7 points)</td>
</tr>
<tr>
<td>2. Present the raw data collected (8 points)</td>
</tr>
<tr>
<td>3. Present calculations and data analysis, and numerical results (10 points)</td>
</tr>
<tr>
<td>4. State the conclusions (5 points)</td>
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</table>

<table>
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<tr>
<th>Summary Statement (5 points)</th>
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<tbody>
<tr>
<td>Write a summary statement discussing what has been learned from the experiment within the context of the concepts of Transport and Rate Processes.</td>
</tr>
<tr>
<td>The pre-lab and lab reports are group submissions.</td>
</tr>
</tbody>
</table>

![Figure 1. Schematic representation of Experimental Setup (a) moth ball, (b) “Arnold Cell” setup for p-dichlorobenzene disc, (c) flow setup.](image)
Numerical results

Diffusion Coefficient

Figure 2 shows a typical graph submitted by the groups showing the data obtained using the naphthalene ball.

As can be seen from the figure, the data follow the trend suggested by Eq. (1). The average diffusion coefficient value for naphthalene across all groups was 0.061 cm²/s, which is in good agreement with the literature-reported value as well as that calculated using the Fuller-Schettler-Giddings equation, shown below:

\[
D_A = \frac{10^{-3}T^{0.55}\left(1 + \frac{1}{M_A + M_B}\right)^{0.5}}{P\left(\Sigma V_a\right)^{0.5} + \left(\Sigma V_b\right)^{0.5}}
\]

where,
- \(M_B\) = molar mass of B (air)
- \(\Sigma V_a\) = sum of diffusion volume of A
- \(\Sigma V_b\) = sum of diffusion volume of B

It should be noted that considerable variation was observed across different groups, and not all groups were able to replicate the linear behavior shown in Figure 2. The values of the diffusion coefficient for naphthalene ranged from 0.01 cm²/s to 0.15 cm²/s. Fewer groups conducted the experiment using p-dichlorobenzene discs. The diffusion coefficients ranged from 0.01-0.06 cm²/s, with the theoretically calculated value being 0.07 cm²/s. This discrepancy between the experimental and theoretical values is attributable primarily to the uncertainty in experimental measurements, including those of mass/characteristic length, and air velocity. Further, the experimental specimens did not conform to the well-defined geometric shapes implicit in the calculations shown above. All the groups were able to identify and present explanations for the discrepancy in their values.

Mass Transfer Coefficient

The mass transfer coefficient values ranged from 0.3 cm/s to 0.85 cm/s for both naphthalene and p-dichlorobenzene. Unlike the diffusion coefficient, mass transfer coefficient is a function of the dimension of the solid, and groups presented their data as a function of time or diameter, as shown in Figure 3.

The experimental values of the mass transfer coefficient were compared to those predicted theoretically using the Frössling correlation shown in Eq. (8), or other applicable correlation depending upon the Reynolds number/Schmidt number ranges.

\[
Sh = 2 + 0.552 \frac{Re^{0.5}}{Sc^{0.5}}
\]

Re = Reynolds number
Sc = Schmidt number
Sh = Sherwood number

The discrepancy in the experimental and predicted values ranged from -20 to -50%, again attributable to the uncertainty of measurements. However, as seen from Figure 3, the mass transfer coefficient increased with decreasing diameter, in accordance with the theoretical predictions.

SUMMARY OF EXPERIENCES

The single most important characteristic that distinguishes this experiment from the rest of the experiments across all undergraduate courses is the absence of a set procedure or apparatus. The students had the total control for designing...
their experimental setup and determining what measurements to make. After some initial apprehension by a few students, most groups readily accepted the challenge. Each group held brainstorming sessions and, working on a tight schedule for the submission of pre-lab, rapidly developed an experimental plan. Most of groups typically submitted their pre-lab reports before the due date, as they were eager to get into the lab to conduct the experiment.

**Summary statements**

The summary statements ranged widely in their length and content. While a few of the summary statements were brief and merely repeated the numerical results, most of the others contained comments related to the experiment and its value in understanding the transport phenomena. Some of the students also conveyed opinions regarding working in the team environment and the utility of this exercise in designing experiments in general. Some of the comments are presented below:

- "Our final lab for transport was an enjoyable project. I particularly liked being able to take our idea and create a wind tunnel..."
- "I think having to find our own materials in the lab and construct our own apparatus was a useful experience that one doesn’t often get in undergraduate labs."
- "This lab also allowed us to be more creative, because we got to make our own apparatuses. This again helped reinforce concepts we were learning in the class."
- "I feel as though I have a strong understanding of the theoretical principles covered in this lab, because of the independence we were given during the procedure."
- "Overall, this experiment helped me understand the concepts from Chapters 26-29 in the Transport book."
- "I learned a lot from this experiment socially and educationally. Working with a team is challenging sometimes, however, a lot of benefits could be harvested from it. One of the main benefits is to simulate the real-world job environment from brainstorming to balancing and checking our mistakes together."

**Instructor observations**

A laboratory experiment should accomplish the following objectives as elucidated by Miller, et al.,[6] and Abu-Khalaf,[7] and re-emphasized by Fogler[8]:

1. Plan the experimental set and measurements to be made
2. Start up and run experiment
3. Collect, analyze, and interpret data
4. Compare experimental results with theoretical predictions
5. Convey the results through clear and concise report and oral presentation
6. Work effectively in teams

The experiment described above meets all of these objectives. Additionally, the students are not merely running the experiment, but actually developing the setup for conducting the experiment. Another important lesson the students learn is that they will frequently encounter a situation where the system they have to work with is not as ideal and well-defined as in the textbooks. However, they will still be required to provide realistic estimates of process parameters that are theoretically consistent. In that sense, this experiment is the closest to what they will come across in their workplace.

Above all, it is the belief of the instructor that any activity assigned to the students must serve to stimulate their thought process and encourage creativity. This experiment can be considered to be a resounding success from this viewpoint. The students were able to respond to the challenge by designing their systems, and interpreting their results based on the theoretical concepts of transport phenomena.

A review of the naphthalene sublimation technique has been presented in the past by Sousa Mendes,[9] and the mass transfer measurements has been explained by Goldstein and Cho.[10] The experiment described herein is a novel implementation of this technique with the objective of motivating the students to learn transport phenomena.

**Future modifications**

The following major modifications will be implemented for reducing errors and improving the experimental accuracy for the subsequent assignments of the experiment.

1. One of the sources of errors is the uncertainty in the velocity around the objects. An anemometer has been procured for use in these experiments for accurate determination of the velocity.
2. The second source of error is the uncertainty in mass/volume measurements. The departure from sphericity becomes quite significant as the naphthalene balls undergo sublimation. Further, the rapid sublimation of both naphthalene and p-dichlorobenzene from samples of relative small initial mass results in amplification of errors in the time derivatives. Using larger samples wherein the rate of material loss is relatively a small fraction of the initial mass will minimize these errors. Highly complex, sophisticated measurement techniques have been proposed in such sublimation experiments, such as using collimated laser light and CCD camera.[11] While such techniques improve the accuracy of measurements, they are expensive and limit the ability of students to be creative with their experiments.
3. An additional concept to be incorporated in the experiment will be that of the boundary layer. Students will be calculating the boundary layer thicknesses from the mass transfer coefficient and diffusion coefficient values. The experimental values will be compared to those predicted using the boundary layer theory.
4. An important component of transport theory is the analogy between the various transport phenomena.
Future experiments will involve modifications for obtaining the heat transfer coefficient and using the experiment to enhance the understanding of various analogies. These modifications will help improve the accuracy of the experimental results and facilitate further understanding of complex concepts in transport phenomena.

CONCLUSIONS
An experiment based on the sublimation of a solid was implemented in the Transport Phenomena course. Students exhibited creative approaches to determine diffusion coefficients and mass transfer coefficients experimentally, and compare the values with theoretical predictions. The experiment proved to be of immense value in helping students understand the complex concepts and increase their interest in the Transport Phenomena course.

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8. Fogler, H.S., Using the senior unit operations laboratory to develop troubleshooting skills and to ease the transition to the workplace, The Academy of Chemical Engineers Lectureship, The University of Missouri-Rolla, MO (2003).

APPENDIX A: DERIVATION OF THE GOVERNING EQUATIONS

Sublimation from solid sphere
The governing equation for steady state diffusion is
\[ \nabla \cdot N_A = 0 \]  \hspace{1cm} (A.1)
Where \( N_A \) is the molar flux of \( A \).
Symmetry considerations in the spherical coordinate system reduce this equation to:
\[ \frac{d}{dr} (r^2 N_{A_r}) = 0 \]  \hspace{1cm} (A.2)
r is the radial direction coordinate and \( N_{A_r} \) is the molar flux in \( r \) direction. For diffusion of \( A \) through stagnant \( B \),
\[ N_{A_r} = -\frac{cD_A}{(1 - y_A)} \frac{dy_A}{dr} \]  \hspace{1cm} (A.3)
Where \( c \) is the total concentration.
Since \( r^2 N_{A_r} \) is a constant [from Eq (A.2)], substituting in Eq. (A.3) and integrating within the limits \( r = R, y_A = y_{A_s} \) to \( r = \infty, y_A = 0 \) yields,
\[ N_{AR} = -\frac{cD_A}{R} \ln(1 - y_{A_{As}}) \]  \hspace{1cm} (A.4)
where \( N_{AR} \) is the flux at the surface of the solid sphere. The mass balance for \( A \) is
\[ 4\pi R^2 N_{AR} = -\frac{d}{dt} \left( \frac{4}{3} \pi R^3 \frac{P_A}{M_A} \right) \]  \hspace{1cm} (A.5)
Substituting for \( N_{AR} \) from Eq. (A.4), and integrating between the limits \( t=0, R = R_{0s} \) and \( t = t, R = R_s \) leads to Eq. (1), when ideal gas law is used to express the concentration.
\[ N_{AR} \] can also be expressed in terms of the mass transfer coefficient \( k_s \),
\[ N_{AR} = k_s c(y_{A_s}) \]  \hspace{1cm} (A.6)
Substituting in Eq. (A.5) leads to Eq. (2).

Sublimation from a cylindrical disc
The solution to transient mass transfer in a semi-infinite medium is given by Welty, et al., as:
\[ W_A = W_{As} S \frac{4D_t t}{\pi} (C_{As} - C_{A_s}) \]  \hspace{1cm} (A.7)
where,
\[ C_A = \text{concentration of A, subscripts S and } \infty \text{ referring to radial positions (surface and far away from surface, respectively)} \]
\[ S = \text{mass transfer area} \]
\[ W_A = \text{moles of A, subscripts t and 0 referring to times} \]
The mass balance on the disc is
\[ 2Sk_s C_{As} = -\frac{d}{dt} \left( Sz \frac{P_A}{M_A} \right) \]  \hspace{1cm} (A.8)
The coefficient \( 2 \) accounts for mass transfer from both the circular surfaces. Again, using ideal gas law for concentration leads to Eq. (4). \( \square \)
Industrial crystallization is a unit operation used to obtain pure solid chemicals of a certain size, usually from multi-component solutions. It can be considered as a method belonging to the fields of particle, purification, and material science. Process control of crystallization principally consists of control of the driving force, i.e., control of supersaturation. The fundamentals of industrial crystallization can be found from various crystallization handbooks such as the Handbook of Industrial Crystallization, edited by Myerson,[1] Mullin’s Crystallization,[2] the Crystallization Technology Handbook, edited by Mersmann,[3] and Davey and Garside’s From Molecules to Crystallizers.[4] Teaching of industrial crystallization fundamentals has covered crystallization applications for both inorganic and organic compounds. Kinetic study of crystal growth from melt in the case of polymer spherulites was introduced by Marentette and Brown,[5,6] and Singfield, et al.[7] Fernández-Torres, et al.,[8] used a solved problem to illustrate the eutectic freeze crystallization method. García-Ruiz, et al.[9] developed a teaching method to obtain large protein crystals by precipitation with the aid of gels.

Crystallization kinetics has a great influence on crystalline product properties such as crystal size distribution and mean crystal size. Thus, crystallization kinetics data is essential for process simulation and design of industrial crystallizers. In addition to conventional off-line measurement methods, crystallization kinetic data can be obtained by real-time Process Analytical Technology (PAT) methods. Real-time process monitoring has developed greatly since the 1990s and many sophisticated methods are now available.

The laboratory exercise introduced in the present work was first implemented at Lappeenranta University of Technology in the early 2000s and has slowly evolved to its current form. The laboratory exercise aims to enhance understanding of what the nucleation rate (generation rate of nuclei, i.e., the increasing number of zero-sized crystals over time) and crystal growth rate mean in practice. In the exercise, a counter-type
inline particle size analyzer is used to monitor and illustrate how the number of crystals increases when nucleation takes place. In addition, the crystal growth kinetics are determined based on a desupersaturation model and by measuring the initial seed crystal size and the crystal size of the final product. The use of chemical engineering calculations and empirical work incorporates elements of constructivist learning, and the use of group work encourages collaborative learning and development of the perspectives of chemical engineering practices.

As we educate students of chemical engineering, at Master’s degree level, our aim as teachers is to provide the ability and skills to design and size various unit operation equipment, in addition to developing an understanding of the fundamentals of unit operations. The crystallization laboratory exercise combines direct experimental measurements and theoretical approaches in which modeling is done based on experimentally obtained data. The results obtained at laboratory scale can be used for industrial scale calculations.

**Pedagogical approach**

The laboratory exercise on kinetics of batch crystallization is based on principles of constructive alignment and collaborative learning. The basic concept is that competencies are generated through cooperation between the students and teachers, and the teachers’ primary role is to facilitate learning.

Constructive alignment is an outcomes-based approach to education that attempts to connect the elements of learning outcomes, teaching methods, and student assessment. It is claimed that by making sure that all of the elements work toward the same goal, institutions can ensure that students’ efforts are appropriate and efficient. When developing the laboratory work, alignment between the intended learning outcomes and student activities was an important aim.

Current engineering education, it has been claimed, does not support learning of many of the skills required of engineers, for example, communication and group working skills. The laboratory exercise aims to address this issue through an approach based on collaborative learning. Thus, the success of one student can help other students to be successful. Collaborative learning fosters students’ development of critical thinking through discussion, clarification of ideas, and evaluation of others’ ideas. It is especially beneficial in enhancing critical thinking and problem-solving skills, which are crucial also in understanding complicated chemical processes that are not readily comprehended at a conceptual level.

**Course overview**

The industrial crystallization part of the Chemical Engineering Unit Operation II course is intended for students in the first year of their Master’s level studies and consists of the following parts: theory, operation, and design of crystallizers; mass transfer of dissolution; and Process Analytical Technology (PAT) in crystallization processes. Learning outcomes of the industrial crystallization part of the course are such that on completion of the module a student can: explain the fundamentals of industrial crystallization (kinetics, solid-liquid equilibrium, population density, crystal size distributions, polymorphism, solvate and hydrate formation, mass transfer in crystallization and dissolution, and real-time process monitoring); list and describe the operation of the most important industrial crystallizers; and estimate the preliminary size of an MSMPR crystallizer. Student learning is assessed by written examination and the laboratory exercise report compiled by each student group. The written examination covers the whole content of the Chemical Engineering Unit Operation II course. Improved examination answers suggest that the laboratory exercise has enhanced students’ understanding of the fundamentals of crystallization kinetics.

In the industrial crystallization module, the teaching methods comprise lectures (8 hours), calculation exercises (12 hours), and the laboratory exercise (4 hours of laboratory measurements, data treatment, and reporting as independent study).

Instructors assist the students in carrying out the crystallization experiments. Instructions given in the supporting information for the course in Appendix I provide further guidance on obtaining crystallization kinetics models by treating the empirical data obtained. Groups of four to five students simultaneously carry out two experimental sets: nucleation rate measurements and crystal growth rate measurements. First, two to three students from the group focus on crystal growth measurements and the other two to three students on nucleation measurements. After completing a number of experiments, the students swap tasks so that every student carries out both nucleation and growth rate measurements and all students investigate both nucleation kinetics and growth kinetics. Each group prepares a report, which is checked by the teacher. To obtain statistically more reliable results, the teacher collects the experimental data acquired by about five groups and distributes all the results back to the groups for further data treatment. A broader range of experimental data enables the obtained data to be treated in a more analytical and critical way. In addition, clearly divergent experimental results can be seen and treated appropriately.

The laboratory exercise is closely linked to other teaching methods used in the course, i.e., crystallization lectures and calculation exercises. The calculation exercises include initial data giving kinetic models of the nucleation rate and crystal growth rate. However, quite often these kinetic data are not available for a specific compound and crystallization system. Therefore, the kinetic data are required to be determined experimentally. The laboratory exercise illustrates a methodology to obtain kinetic data required for crystallizer design. Furthermore, the introduced laboratory exercise can be used efficiently with moderate teaching load for crystallization courses with a relatively high number of participating students.
TABLE 1

Obtained parameter values fitted from experimental data of nucleation kinetics

<table>
<thead>
<tr>
<th>dN/dt</th>
<th>Calculated B</th>
<th>Initial temperature °C</th>
<th>Final temperature °C</th>
<th>ΔT °C</th>
<th>Δc kg KDP/kg H2O</th>
<th>log(Δc)</th>
<th>log(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>2.48x10^5</td>
<td>23.0</td>
<td>15.0</td>
<td>8</td>
<td>0.035</td>
<td>-1.46</td>
<td>5.39</td>
</tr>
<tr>
<td>0.18</td>
<td>1.81x10^5</td>
<td>23.2</td>
<td>17.2</td>
<td>6</td>
<td>0.027</td>
<td>-1.57</td>
<td>5.26</td>
</tr>
<tr>
<td>0.12</td>
<td>1.20x10^5</td>
<td>23.0</td>
<td>18.0</td>
<td>5</td>
<td>0.023</td>
<td>-1.65</td>
<td>5.08</td>
</tr>
<tr>
<td>0.10</td>
<td>1.04x10^5</td>
<td>23.0</td>
<td>19.0</td>
<td>4</td>
<td>0.018</td>
<td>-1.74</td>
<td>5.02</td>
</tr>
</tbody>
</table>

Figure 1. Count rates (number /s) of KDP crystals monitored by the MTS PSyA laser reflection particle size analyzer over time with subcooling of 5 °C.

In our courses, the student number has varied typically between 20 and 30 students and all the laboratory exercises of the groups have been carried out within one week.

EXPERIMENTAL PROCEDURE

A harmless inorganic salt—potassium dihydrogen phosphate (KDP)—is used as the model compound and water is the solvent. The crystallization temperatures are close to room temperature, so there is no risk that students may handle hot samples. KDP is crystallized by cooling from an aqueous solution, because the salt is relatively soluble in water and its solubility is higher at higher temperatures. The laboratory exercise focuses on nucleation and crystal growth kinetics: how the nucleation rate and crystal growth rate can be determined in laboratory scale systems.

Nucleation rate models

Nucleation rate study is based on online count number measurements by an MTS PSyA laser reflection particle size analyzer. Particle size analyzers are the most expensive equipment used in the laboratory exercise at a price of roughly €50 000 per unit. A curve of nucleus count numbers with time can be obtained for a known subcooled degree. An example is shown in Figure 1. In the exercise, each student group uses a different undercooling degree, which means supersaturation differs and more data are available, enabling more accurate parameter fitting. Based on data from all groups with a subcooled rate between 4 and 8 °C, parameters k₈ and i can be estimated by fitting the data to Eq. (1).

Examples of experimental and predicted results are shown in Table 1 and Figure 2. An expression for nucleation rate B obtained by fitting measured data of an earlier laboratory exercise for KDP is shown in Eq. (1):

\[
B = 2.92 \cdot 10^7 \Delta c^{0.42}
\]

where B is the nucleation rate and Δc is the supersaturation degree based on the difference between the actual salt concentration and the equilibrium concentration of the saturated solution taken from solubility data.

Crystal growth rate models

Crystal growth can be illustrated by measuring crystal size distribution over time directly during the batch process. In this system, the supersaturation level varies to some extent over time. An indirect desupersaturation curve method can be used for estimation of the crystal growth rate at different supersaturation degrees versus time. The model of the desupersaturation curve derived by Garside, et al.* consists of the terms shown in Eqs. (A5)–(A10) in Appendix 1.

RESULTS

Based on available literature, solubility data, and experimental data obtained by crystal size measurement and desupersaturation method by all groups with a subcooling range
between 3.5 and 6 °C, Eqs. (A5)-(A10) are used and parameter values are obtained by least square method. Parameter values for the models of crystal growth rate are given in Table 2.

Two crystal growth models, explained in more detail in Appendix 1, are used to investigate crystal growth mechanisms:

**A.** The crystal growth rate mechanism dominated by surface nucleation based birth and spread (B+S) [Eq. (A3)]

\[ G_{B+S} = A_{B+S}(S-1)^{5/6} \exp[-B_{B+S}(S-1)] \]

**B.** Burton-Cabrera-Frank (BCF) model (screw dislocations on the crystal surface as the crystal growth step) [Eq. (A4)]

\[ G_{BCF} = A_{BCF} \left[ \frac{(S-1)^{7/6}}{B_{BCF}} \right] \tanh \left[ B_{BCF} / (S-1) \right] \]

The student groups use Eqs. (A3) and (A4) to draw conclusions about the crystal growth mechanism. Better fitting shows if crystal growth is taking place by birth and spread mechanism or via screw dislocation mechanism. The experimental and predicted results by the two methods are shown in Table 2 and Figures 3. Based on the differences between experimental and modeling results in Figure 3A and Figure 3B, it can be seen that the deviations by desupersaturation method are smaller in Figure 3B. Therefore, it can be concluded that better crystal growth rate data as a function of supersaturation are obtained by desupersaturation method than by direct crystal growth rate measurements. Moreover, based on sum values of squared residuals obtained by BCF and birth and spread growth models, BCF model is concluded to be a slightly more appropriate expression for crystal growth of potassium dihydrogen phosphate.

Course feedback of students was collected via Webropol online survey software when the course was over. Aspects of the course were graded on a scale 1 to 6 (1 - poor; 6 - excellent). Average values from 24-25 feedback responses were: “Instructions of the laboratory work were clear and understandable” – 4.04; “Guidance during crystallization measurements was good” – 4.71; “The laboratory work impacted my learning of crystallization kinetics fundamentals” – 4.24; “The teamwork was useful” – 4.28; and “Process Analytical Technology based in-line process monitoring (count rate measurements with MTS PsyA)” – 4.42. As can be seen from the feedback, the students gave the highest grade for guidance during the laboratory work and learning of Process Analytical Technology was considered useful. As a summary, in the eyes of the students, the laboratory exercise has proven to enhance learning of fundamentals of industrial crystallization and the students feel that they can use appropriate analysis methods in practice.

### CONCLUSIONS

A laboratory exercise for learning crystallization kinetics was introduced. The students carried out the studies in student groups of four to five students, which allowed the whole course group of 20-30 students to undertake empirical investigations, which were further utilized in data treatment calculations to estimate crystallization kinetics models.

### ACKNOWLEDGMENTS

The authors gratefully acknowledge the Academy of Finland (project 260141) for financial support.
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APPENDIX 1. SUPPORTING INFORMATION: INSTRUCTIONS FOR LABORATORY WORK

Introduction

Crystallization kinetics data can be used for design and sizing of industrial crystallizers and for selection of the operational conditions of a crystallization process. Crystal size distribution and the shape of the final crystalline product (the quality of the product) are mainly determined by the nucleation rate and crystal growth rate.

The laboratory exercise introduces a methodology to determine crystallization kinetics. Crystallization is initiated when nuclei (cluster of molecules of visible or detectable size) are formed in a supersaturated solution. This process is referred to as nucleation. The formed nuclei grow larger as long as the solution, i.e., mother liquor, is supersaturated. The exercise comprises two parts; nucleation kinetics and crystal growth kinetics. The crystallization method used is cooling crystallization.

Model compound

Potassium dihydrogen phosphate, KH₂PO₄, and water as a solvent are used as the model system. The solubility data of KDP in water at different temperatures is needed to determine the driving force degree, i.e., supersaturation, usually expressed by the difference between actual concentration and equilibrium concentration. KDP crystals are assumed to be cubic, the density of KDP crystals is 2340 kg/m³, and the solubility of KDP can be taken from the literature.[3]

Nucleation rate

Nucleation rate B is a kinetic parameter presenting the generation rate of zero-sized nuclei per unit volume. The nucleation rate depends on supersaturation, mixing conditions in the stirred tank and the suspension density, i.e., kg crystals per unit volume. In this laboratory exercise we investigate the nucleation rate of the cooling crystallization system as a function of supersaturation, Δc, as shown in Eq. (A1)[2]:

\[ B = k_{n} \Delta c \]  \hspace{1cm} (A1)

where

- \( k_{n} \) constant
- \( \Delta c \) supersaturation, which is the difference between concentration \( c \) and solubility \( c^* \)
- \( i \) constant
- \( B \) nucleation rate, number of nuclei \( m^{-3} \cdot s^{-1} \)

Crystal growth rate

The growth rate of a crystal is affected by many factors, such as supersaturation, mixing conditions, impurities present in the solution and additives. The section below shows commonly used equations and models for the crystal growth rate.

Kinetics of crystal growth can be described with a semi-empirical equation shown in Eq. (A2)[3]:

\[ G = k_{G} \Delta c^{i} \]  \hspace{1cm} (A2)

where

- \( G \) linear crystal growth rate, \( m \cdot s^{-1} \)
- \( k_{G} \) \( m \cdot s^{-1} \) constants

A model of the crystal growth rate mechanism has been introduced for crystal growth systems dominated by surface nucleation based the birth and spread model (B+S model). This model allows the spreading of nuclei at a finite constant rate that is assumed to be independent of crystal size. It also assumes that nuclei can form at any location, including in incomplete layers, and that there is no inter growth between the nuclei. The simplified expression of this model is[1,15]:

\[ G_{b+s} = A_{n,s} (S-1)^{i} \exp[-B_{b+s} / (S-1)] \]  \hspace{1cm} (A3)
The following model has proven to be appropriate for crystallization systems in which crystal growth rate is dominated by screw dislocations on the crystal surface. According to the Burton-Cabrera-Frank (BCF) model, screw dislocations in the crystal are the source of new growth steps and crystal growth from these steps can occur continuously. In this model, surface diffusion is assumed to be the determining rate. The simplified expression can be described as:

\[ G_{BCF} = A_{BCF} \left( \frac{S-1}{B_{BCF}} \right) \tanh \left( B_{BCF} / (S-1) \right) \]  

where

\[ A_{BCF}, B_{BCF} \] constants

\[ G_{BCF} \] crystal growth based on BCF model

The crystal growth rate as a function of supersaturation can be determined by the batchwise desupersaturation curve technique introduced in the Handbook of Industrial Crystallization \(^{11}\) and by Garside, et al., \(^{14}\) who presented a detailed description of the evaluation of crystal growth kinetics from a desupersaturation curve, shown in Figure A1, using initial derivatives. Only size-independent growth is considered. Growth rate dispersion is assumed to be negligible, and crystallization conditions are taken to be isothermal. For a batch crystallizer, mass deposition as a result of nucleation is negligible. The crystal growth kinetics can be computed with Eqs. (A5) to (A10).

\[ G = \frac{R_{c} \beta}{3 \alpha \rho} \]  

\[ R_{c} = k_{s2} \Delta c_{0} \Delta \xi \]  

\[ g^2 = \frac{2 \beta \Delta c_{0}}{3 \alpha \rho \xi} + \frac{\Delta c_{0} \Delta \xi}{\Delta \xi_{0}} \]  

\[ k_{s2} = -\frac{\Delta \xi}{A_{T} (\Delta \xi_{0})^{\gamma}} \]  

\[ A_{T} = \frac{6 m_{s0} \left[ c^{c} (T_{0}) + 1 \right]}{\rho \bar{I} \rho_{s} \rho_{w} \bar{x}_{s} \bar{c}_{w}} \]  

\[ \Delta c = a_{0} + a_{1} t + a_{2} t^{2} \]  

where the values of \( \Delta c_{0} = a_{0}, \Delta \xi = a_{1}, \) and \( \Delta \xi_{0} = 2a_{2} \) can be obtained from the fitted equation of the desupersaturation curve.

Experimental measurements

Nucleation kinetics

An MTS PSyA laser reflection particle size analyzer is used to characterize the nucleation rate. It is assumed that the number of nuclei is directly proportional to the count rate increase of the PSyA analyzer, and the sampling volume of the analyzer is 1 ml. Nucleation kinetics of potassium dihydrogen phosphate, KH\(_{2}\)PO\(_{4}\) (KDP) from water is studied. A saturated solution of KDP at room temperature is used in the experiments. Mixing intensity, which is supported by an up-pumping 4-pitched-blade turbine, is kept constant during the crystallization operation.

The experimental procedure is as follows:

1) Add 2.5 liter saturated KDP solution to a jacketed mixing tank.

2) Heat the solution 4°C above the saturation temperature. Keep the temperature constant for 10 min.

3) Cool the solution _°C below the saturation temperature and initiate nucleation by adding 0.2 g KDP seeds to the solution.

4) Measure the count rate by MTS PSyA online probe until a constant level is reached.

5) Each group should measure a single data point. All data points obtained by the different groups are used in the calculations.

By assuming the count rate increase of the PSyA analyzer, \( dN \) (number/s) is directly proportional to the number of nuclei in the solution, and the analysis volume is 1 ml, the nucleation rate \( B \) (number m\(^{-3}\) s\(^{-1}\)) can be calculated as:

\[ B = \frac{dN}{dt} \bar{V}_{\text{analysis}} \]

After obtaining the nucleation rate at different supersaturation
levels, the parameters in Eq. (A1) can be obtained by fitting the measured data to the equation.

**Crystal growth rate**

**Crystal size measurement (batch crystallization)**

A saturated solution of KDP at room temperature is also used for investigating kinetic growth of KDP from water. Mixing is provided by an up-pumping 6-pitched-blade turbine, and the mixing intensity is kept constant for all experiments.

1. Weigh 300 g saturated solution into a 250-ml glass vessel. Heat the solution 4 °C above the initial temperature.
2. Cool the solution °C below the saturation temperature following the teacher’s instructions. The solution should be clear and primary nucleation before seeding has to be avoided.
3. Weigh 0.3 g seeds of KDP Add the seeds to the supersaturated solution. Let the crystals grow for 30 min. Simultaneously, measure the electrical conductivity as a function of time. (Record the conductivity at every minute.)
4. Filter the crystals.
5. Measure the crystal size distribution of the seeds and final crystals with the Beckman Coulter LS 13320 laser diffraction analyzer. The background solution is ethanol. (KDP is poorly soluble in ethanol.)
6. Each group should measure a single data point. All data points obtained by the different groups are used in the calculations.

**Crystal growth rate based on desupersaturation method**

Derive the desupersaturation curve from the measured conductivity data. Here, it is assumed that the electric conductivity is linearly dependent on concentration over the studied concentration range. In addition, the initial and final concentration of the solution is assumed to be the saturated concentration at room temperature and the corresponding subcooled temperature. The parameters where y is concentration and x is conductivity, can be obtained from the initial and final measured conductivity values and from the studied concentration range. The concentration range can be obtained from the used temperature range and solubility data. The whole supersaturation profile can then be computed with Eq. (A11).

**Data treatment of obtained results**

**Data treatment for nucleation rate**

Kinetic parameters \( k_n \) and i in Eq. (A1) are calculated by parameter fitting (method of least squares). Obtained results of experimental data and parameter fitting are shown in Figure 2 and Table 1.

**Data treatment for crystal growth rate**

Two different methods are used to find crystal growth rate as a function of supersaturation: \( \Delta L/\Delta t \)-method and desupersaturation method. Methods are described in detail below. Obtained results of experimental data and parameter fitting are shown in Table 2 and Figure 3.

**\( \Delta L/\Delta t \)-method**

In the \( \Delta L/\Delta t \)-method, average size change over time is measured. \( \Delta L \) is the difference between seeds and sample cumulative size distribution (median size at 50% of cumulative size distribution), and \( \Delta t \) is the measurement time. The method does not take into account the decrease of supersaturation during the measurement.

**Desupersaturation method**

The measured conductivity is converted to concentration and further supersaturation by linear fitting. Crystal growth rates are calculated from the fitted equation of the desupersaturation curve.

**Report**

Each group prepares a report that includes a description of the experimental procedure, testing equipment and experimental data, processing of the test data and results of measurements, and a conclusion and discussion. The teacher will assess the report and demand corrections if necessary.

The following elements form the major parts of the report.

1) Description of the experimental setting.
2) Solubility of KDP as a function of temperature.
3) Measured results:
   i. Supersaturations as concentration difference.
   ii. Nucleation rates with different supersaturations.
   iii. Measured growth rates for different supersaturations and crystal sizes.
4) Calculations:
   i. Find \( B = f(\Delta c) \) and fit parameters \( k_n \) and i in Eq. (A1).

<table>
<thead>
<tr>
<th><strong>TABLE A1</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>( \Delta L/\Delta t ) method and desupersaturation method of calculating crystal growth rate</strong></td>
</tr>
<tr>
<td>( \Delta L/\Delta t )</td>
</tr>
<tr>
<td>( \Delta t ) is the measurement time.</td>
</tr>
<tr>
<td>( \Delta c ) is conductivity; ( t_0 ) and ( t_{\text{end}} ) are initial time and ending time, and ( T_0 ) and ( T ) are initial and final temperature, respectively.</td>
</tr>
</tbody>
</table>
ii. Find $G = f(\Delta c)$ with two different methods, that is, the crystal size method ($\Delta L/\Delta t$) and the desuper-saturation method (see Table A1) and compare the results. Any method for parameter fitting can be used, however use of the least square method is recommended. Fit the obtained data of concentration as a function of time to the desupersaturation model. Fit the obtained data of crystal growth rates as a function of supersaturation to Eqs. (A3) and (A4). Compare the obtained fitting results to determine the crystal growth mechanism.

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DEVELOPMENT OF INTERACTIVE VIRTUAL LABORATORIES TO HELP STUDENTS LEARN DIFFICULT CONCEPTS IN THERMODYNAMICS

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INTRODUCTION

Virtual laboratories are receiving attention as an alternative way to engage students and promote learning as technology becomes more integrated into classroom instruction. Physics educators at the University of Colorado have developed a set of virtual laboratories they call PhETs that allow students to explore representations of physics phenomena, some of which are impossible to view in a laboratory environment. The PhET simulations are designed to allow students to construct their own understanding of physics and are useful as a part of learning activities in class. PhET simulations are open ended, so learning activities need to guide, but not constrain, students using them. Research on this type of virtual laboratory has shown that it significantly improves learning.

We have designed the Interactive Virtual Laboratories (IVLs) to target important engineering concepts, similar to what PhETs provide for physics education. However, unlike PhETs, the Interactive Virtual Laboratories are explicitly scaffolded. They are not open-ended sandbox environments, although they do allow some level of experimentation. Instead, students are guided by prompts and must answer numerical and discussion questions to proceed. Students are expected to interact with the simulations in intentional ways to gain understanding and answer questions. The approach taken in designing them was to target a specific thermodynamics threshold concept in each simulation.

Meyer and Land introduced threshold concept theory as a way to view learning and curricular progression. They describe threshold concepts as concepts critical for understanding a topic. Without this understanding, a learner cannot progress. Their definition of threshold concepts differ from...
“core concepts,” or conceptual building blocks that progress understanding of a subject, by specifying four main features of threshold concepts: transformative, irreversible, integrative, and troublesome. Threshold concepts are transformative because they create a significant shift in how learners perceive subjects on a fundamental level, sometimes even leading to a transformation of personal identity. They are irreversible because learners are unlikely to forget their shifted perspectives after crossing a threshold. They are integrative because they expose the previously hidden interrelatedness of subject knowledge. Finally, they are troublesome in that they are conceptually difficult for students to learn, often yielding counterintuitive or unexpected results. In engineering, there is recent attention to curriculum development based on identifying threshold concepts, but we must also be aware that many instruction approaches do not fundamentally reform faulty student assumptions. We propose that threshold concept theory is a useful framework for identifying topics for Interactive Virtual Laboratories, and Interactive Virtual Laboratories are useful tools for enabling students to learn threshold concepts.

We identified a broadly defined set of threshold concepts for the Interactive Virtual Laboratories that range from misconceptions of first principles to capabilities needed to solve problems. These threshold concepts include understanding hypothetical paths, the difference between reaction rate and equilibrium, the difference between constant pressure and constant volume heat capacities, the conditions necessary for a reversible process, and the mechanism through which pressure-volume work adds energy to a system. The last two threshold concepts are the focus of the current study. We chose these threshold concepts based on information from three sources. First, we analyzed student written responses to conceptual questions using a database system, leading to an identification of common misunderstandings. Second, we referenced the literature on misconceptions in chemical engineering and physics as a basis to confirm our identification of threshold concepts. Third, we used the last author’s domain knowledge and twenty years of experience teaching thermodynamics to identify threshold concepts.

Elby examined reasons why physics students often study in unproductive ways, such as focusing on memorizing equations and solution algorithms, rather than gaining a deep understanding of physics. He surveyed 106 college physics students, asking how they study for class in order to do well in the course. Furthermore, he asked them to compare their study methods with how they would study if they were only interested in learning physics deeply, without grade pressure. He found that many students use rote-based study methods because they believe it will help them on exams, even when they are aware that they are not learning the material in a way useful for real-life application. In developing the Interactive Virtual Laboratories, we took a highly conceptual approach.

To correctly answer problems, specifically discussion questions, students must use conceptual understanding to synthesize data. A rote understanding leads to incorrect numerical answers and poor discussion answers.

Two research questions are addressed in this study:

(i) How does the way students engage with the simulations affect how they comprehend the targeted threshold concept: Do they complete the simulations with a singular focus on equations and variables, or do they use a more conceptual approach by solving problems using the information depicted in the simulation display and graphs?

(ii) How do students perceive the simulations: Do they view them as useful learning tools, and what recommendations do they make for them?

INTERACTIVE VIRTUAL LABORATORIES

The Interactive Virtual Laboratories are a series of two-dimensional simulations designed to address targeted threshold concepts. They are available for instructors to use through the AIChE Concept Warehouse website (<http://cw.edudiv.org/>). They were developed following design principles for educational multimedia. We used Mayer’s approach involving cognitive load theory, which asserts that students have a maximum information processing capability. Excess information overloads the student’s learning channels and reduces information processing. We also incorporated the findings of Scalise et al. from a synthesis of the results of 79 studies of virtual laboratories to find best practices for virtual laboratory design, including an emphasis on focal points rather than step-by-step instructions, basing design to minimize cognitive load, and introducing scaffolding with fading. Finally, we kept in mind the design principles suggested by Mayer and Moreno:

- **Multiple representation principle**: Explanations in the form of a combination of words and pictures are more effective than words or pictures alone.
- **Contiguity principle**: Simultaneous presentation of words and pictures works better than presentation in succession.
- **Spatial contiguity principle**: Closer proximities of text and image enhance the learning outcome.
- **Personalization effect**: Deeper learning can be achieved by conversational style text rather than formal style text.

The IVLs are written in JavaScript and HTML for easy incorporation into student laptops and web browsers. They make use of the HTML5 Canvas element to draw two-dimensional objects for simulating molecular behavior. Each simulation depicts ideal gas molecules as perfectly elastic spheres. Individual labs consist of examining the effect of different processes on the molecules, such as compressing
or heating them, while performing numerical computations and answering discussion questions. Each individual simulation targets a single threshold concept and adheres to a scaffolded design following the predict-observe-explain technique proposed by Gunstone and Champagne. Before interacting with the simulation, students are asked to predict what will happen if they make a change, such as raising the temperature or increasing pressure. Students then perform and observe the virtual experiment and, afterwards, explain if their prediction was accurate and what effects the change had using information present in the simulations. The goal of the simulations is to allow students to describe molecular and macroscopic thermodynamic phenomena in terms of the underlying physical behavior using conceptual knowledge. In real experiments, students cannot see molecular interactions, and their understanding often becomes abstract and removed, existing only in the form of equations. The Interactive Virtual Laboratories allow students to see how molecular interaction gives rise to the phenomena described by mathematical equations. This paper focuses on how students use two IVLs, one based around the thermodynamics threshold concept of pressure-volume work and the other on that of reversibility.

1. **Pv Work.** Work is an abstract concept, and it is often difficult for students to understand how the act of doing work on a system adds energy. Intuitively, students may understand that compressing a gas causes it to undergo an increase in temperature, or a "heating up." The purpose of the work simulation is to give students a physical model explaining why doing work on a gaseous system adds or removes energy from a physical and molecular perspective, ultimately showing students that work adds energy through an exchange of momentum and kinetic energy between a system and its surroundings. Students develop the understanding that a moving, perfectly elastic sphere colliding with a wall moving towards it rebounds with a speed greater than if the wall had been stationary. By using this simulation, students can apply their knowledge of elastic collisions to thermodynamic work.

From the equation above we see that temperature increases as we do work by decreasing volume. Temperature is an expression of molecular kinetic energy, so as the system is compressed, the molecules must speed up. These ideal gas molecules can be thought of as perfectly elastic bouncy balls. Using the movable wall above, can you determine what event causes the molecule's speed to change? Can you explain why that would cause a temperature change in many molecules?

\[ n c_0 \Delta T = -P_{ext} \Delta V \]

**Figure 1.** Screenshot of the single molecule in a closed container. The top wall can be moved by clicking and dragging the arrow to the right of the container. The molecular speed is displayed with every wall collision and changes when colliding with a moving wall.
Previously you answered that the compression did 12 KJ on the system bringing it to a final temperature of 735 K. Here’s the same compression, but this time we’re displaying work done and temperature. How do the results compare? If there’s a discrepancy, can you account for it?

Type your answer here.

2. Reversibility. The purpose of the reversibility simulation is to give students a physical model to show the difference between reversible and irreversible processes. Often, students assume real processes can be approximated as reversible when such an assumption is inappropriate. The simulation goal is to show students the conditions necessary for a system to be reversible and help students see when assumptions of reversibility are appropriate. Similar to the Pv Work simulation, the Reversibility simulation takes a progressive understanding approach and primarily consists of a series of isothermal piston and cylinder assembly systems. Students are asked to compress and expand the system between two different states several times. Each time they perform the process, they do it in a greater number of steps. Ultimately, students are expected to understand the difference between reversible and irreversible processes.
to see that a system must always be in equilibrium with its surroundings for a process to be reversible, meaning only differential changes in input are allowed. Another result is that a process approaches reversibility as it is performed in a greater number of steps with smaller step size.

The simulation starts with a compression process in a single step, as shown in Figure 3. Students are asked to compress an ideal gas system by placing a single block on a piston and allow it to come to rest. Students then expand the piston by removing the block. Students are able to see that the process is irreversible, as the amount of work done on the system initially is not what is gotten out during expansion.

Next, students compress the system using two steps instead of one, and the same is repeated for expansion. Students are expected to see that it requires less work to compress the system to the same final state in two steps than in a single step under constant pressure. They are also expected to see that more work is done by the system when it expands in multiple steps.

Students then perform one more compression and expansion. However, this time they are given very small grains of mass to place on the piston as shown in Figure 4 (following page). This process is supposed to be approximately reversible, as the amount of work required to compress the system is equal to the work done when the system expands. Students are expected to see that the process approaches reversibility as the number of steps increase and the changes in input become infinitesimal.

The Reversibility simulation shows that reversible processes must always be in a state of equilibrium and therefore require an infinite number of infinitesimally small steps to complete.

METHODS

Eight individuals took part in the study described in this paper: four third-year students and four fourth-year students. Seven of the eight students were undergraduates in chemical engineering while one was an undergraduate in mechanical engineering.
engineering at the time of the study. All had taken at least one undergraduate course in engineering thermodynamics. The study was approved by the IRB and all students signed informed consent forms.

Participants completed either the Work or Reversibility IVL. An interviewer observed participants while completing the simulation. Students had access to a chemical engineering thermodynamics textbook, *Engineering and Chemical Thermodynamics*,[16] and the internet while completing the simulations. We used video screen capture technology to record the screen and audiotape the students working on the simulation. We used a “think aloud” protocol where students verbally described their actions and thought processes while working. Interviewers did not answer any questions directly related to the topics covered in the simulations. However, they did answer general questions about the simulations and interview process as well as asking participants to explain their actions if unclear. Students who ran into difficulties with a question and were unable to answer it were told to make a guess and continue.

After completing the simulation, students were asked a series of questions assessing how well they understood the material and asking for feedback on the simulation design. The interviewer first asked for general impressions and feedback for the simulation in addition to asking what the participant thought was the main point of the simulation. The interviewer asked the students questions about their thoughts on the simulation: the usability, usefulness for learning, and ways they might be incorporated into classes. Interviewers also asked students to compare their performance and learning in two different chemical engineering thermodynamics classes, one that uses a traditional lecture-based format and one that incorporates technology-assisted active learning pedagogies. Finally, interviewers asked a conceptual question relating directly to the main purpose of the simulation. On Work, students were asked to describe the mechanism through which PV work adds energy to a system. On Reversibility, students were asked what conditions are necessary for a process to be reversible.

*Figure 4. An approximately reversible compression using differential sand elements. Sand is placed on or removed from the piston using the buttons to the right of the piston.*
To answer the first research question about how students engage with the Interactive Virtual Laboratories, we examined the recordings of students completing the simulations as well as the transcribed post-simulation interviews. We looked specifically at the section of the simulation where the main conceptual idea was introduced to see if the student gained a conceptual understanding of the physical phenomenon. We also tried to see how the student went about making sense of the information. We compared these data to how the student answered the conceptual question at the end of the interview to see if the student retained the information if they understood it at first or if they managed to make sense of it later if they did not.

To answer the second research question about student perceptions of Interactive Virtual Laboratories, we analyzed the transcribed post-simulation interviews. We looked specifically for statements where the participant indicated a feature of the simulations that was particularly useful or confusing. We also looked for suggestions made by the students to help improve the simulations.

RESULTS

The approach students took to complete the simulations can be generally divided into two distinct groups: equation-based and concept-based. The IVLs were designed to elicit a concept-based approach in students. The reasons some students used an equation-based approach and its effect on their learning when using the simulations is of particular interest to us. In general, students who used a concept-based approach focused largely on the physical phenomena being modeled by the simulations and used the data generated by the simulation to formulate explanations during the discussion questions. On the other hand, students who used an equation-based approach focused on finding an equation that mathematically relates variables while answering the discussion questions, often without noticeably giving attention to the pertinent physical phenomena. Of course, none of the students used an approach that was solely concept-based or equation-based. Some participants switched approaches depending on the question being asked; others switched from equation-based to concept-based when they found that the former was not sufficient to complete the simulation satisfactorily.

In the following explorations of simulation use, we use select quotations to illustrate student thinking and reasoning. Additional quotes are presented in Appendix A of reference 17, which provide insight into how students engaged with the most conceptual portions of the simulation, along with additional feedback and suggestions for simulation improvements.

PV WORK

Perhaps the most illustrative example of the contrasting equation-based and concept-based methods is the different ways Alfred, David, Beverly, and Carl completed the single molecule simulation on Pv Work. The single molecule simulation allows students to experiment with a single molecule in a closed container and shows them that work adds or removes energy from a system through an exchange of momentum and molecular kinetic energy. The purpose is to give students a way to figure out for themselves what causes the energy and temperature to change, instead of making them guess using abstract ideas about molecular kinetics.

Alfred

Alfred’s approach to the single molecule was highly concept-based. He noticed that the molecule speeds up when it collides with the wall, as shown in the following quotation:

“Oh, it’s when it hits the moving wall. That’s what will cause it to speed up because when the wall’s moving, it smacks into it […] and when I don’t move the wall, the thing doesn’t change speed because all of the collisions are perfectly elastic. That makes sense.”

From this statement, we can see that Alfred notices that the molecule speed only changes when the molecule collides with a moving wall. A stationary wall does not lead to a change. Alfred also explains how this information can be applied to the temperature change in a system of many molecules:

“It causes a temperature change in many molecules because it increases the average speed of all the molecules distributed inside the container when they all hit the slowly approaching wall.”

Alfred also answered the final conceptual question during the interview correctly, indicating that he was able to use the simulation to understand the main threshold concept.

David

David, similar to Alfred, also used a concept-based approach when completing the single molecule simulation. He noticed how momentum was transferred during the collision with the moving wall. He responded to the final conceptual question as follows:

“So when you change the volume, that’s doing work. And so that is introducing momentum that is transferred to the molecules which adds kinetic energy which gives them a higher internal energy, which then changes the internal temperature.”

This response indicates that David understood the threshold concept and related it to the simulation.

Beverly

In distinct contrast to Alfred and David, Beverly used a largely equation-based approach when completing the single molecule simulation. In this example, we can see that she focuses on the ideal gas law in a situation when its use is inappropriate:

“Well it speeds up when you have a smaller space, so does the ideal gas law matter? Is that what they’re trying to talk about?”
She states that the molecule’s speed increases as the volume is decreased. However, this is not necessarily the case. She does not comment on the fact that the molecule only speeds up during a collision with the moving wall. If the volume decreases without the molecule making contact, then the molecular speed stays constant. Beverly did attempt to take a concept-based approach after she became aware that the ideal gas law could not provide a sufficient explanation:

“When the molecule collides with the walls, the speed will increase, and when there is a smaller space, there are more collisions.”

Unfortunately, she confused the temperature dependency on molecular kinetic energy with a dependency on “number of collisions.” During the final conceptual question, Beverly attempted to give an answer before withdrawing it, stating that she did not know.

Carl

Carl took a solely equation-based approach to the single molecule simulation, unlike Alfred and David who successfully took a concept-based approach, and Beverly who tried a concept-based approach unsuccessfully. He attempted to explain the phenomena using an open-system energy balance:

“Energy of the system is delta U over dt plus delta of kinetic energy over t plus delta of potential energy over time, and that’s equal to heat plus work. And this is an adiabatic process, so heat is zero.”

Carl does not take into account that he is not using an open system. He also confuses the macroscopic kinetic energy term in the balance with molecular kinetic energy. Similar to Beverly, Carl realizes that his reasoning is insufficient to explain what causes a temperature change and says that he does not know the answer. He also provided an incorrect answer during the final conceptual question.

We cannot determine what exactly causes students to take one of the two general approaches, but it appears to depend largely on the student’s predisposition. Student orientations are fairly robust; students who customarily take an equation-based approach will continue to do so when completing the IVLs unless something forces them to take a concept-based approach. However, Beverly and Carl show that students who take a largely equation-based approach are not rewarded. Instead, the IVLs force a conflict in these students. They try to generate an explanation but realize that they are incapable of understanding the threshold concept, as demonstrated by Beverly and Carl’s lack of confidence when answering conceptual questions. In addition, the IVLs do, as is seen with Alfred and David, reward students who take a concept-based approach by helping them understand difficult threshold concepts. This information shows that to be fully successful, the IVLs should better address those students who take equation-based methods.

REVERSIBILITY

Student approaches also differed in the reversibility simulation. However, three out of the four students were able to answer the final conceptual question correctly. The approaches taken by Elaine, Frank, George, and Henry during the Reversibility simulation were less distinct from one another than the students who completed the Work simulation, so closely examining each student is less helpful here. Instead, we will briefly go over what type of approach each student took and then compare it to how they answered the final conceptual question.

Elaine

While doing the simulation, Elaine was the only person to use the differential definition for work without looking in the textbook. In this way, she was the only one to take a concept-based approach from the start of the simulation. However, she was also the only participant to incorrectly answer the final conceptual question. Her answer may have been due to some confusion, as instead of describing the conditions necessary for a reversible process to take place, she simply gave the definition of a reversible process.

Frank, George, and Henry

Frank, George, and Henry all initially used equation-based approaches. All three looked in the book to find an applicable equation for the single-step compression process. While Frank and George correctly used the equation to find work done under constant pressure, Henry used the equation for reversible work. However, after seeing the two-step process, Henry realized he had made a mistake and went back to use the correct equation. After completing the simulation, all three were able to correctly answer the final conceptual question. The fact that all three understood the threshold concept covered in the simulation shows that they were able to use a concept-based approach to synthesize the physical information, at least when answering discussion questions.

DISCUSSION

After seeing some of the ways students approached the simulations, we need to consider why the Reversibility simulation is more effective in explaining the threshold concepts than the Pv Work simulation. One explanation is based on the freedom granted by each of the simulations. The Work simulation uses minimal scaffolding during the single molecule simulation. Students are allowed to experiment with the container and molecule and are expected to answer a discussion question. However, they are only required to hit the molecule once before proceeding to the next question. Students are supposed to create their own understanding when this is happening. The prompt also does not thoroughly explain molecular kinetic theory, so students may not fully understand that the gaseous system temperature is a function of the average molecular kinetic energy. On the other hand,
the Reversibility simulation is highly structured. The students cannot interact with the simulation more than was intended; they can only place or remove mass from the piston. The progressively more complicated processes also act as checks for students who have answered incorrectly. As was seen with Henry, someone who treats the single-step process as reversible will realize his mistake when he sees that the two-step process must be different.

This simulation data appears to show that the most effective simulations for teaching threshold concepts are those that are highly scaffolded and provide progressively more complex systems. These design elements keep students from straying too far from the desired threshold concept while also giving students a way to compare their answers from previous questions to new situations and see how they compare. However, this assertion is based on limited data and is different than what other researchers have suggested. More investigation is warranted.

STUDENT FEEDBACK

Student feedback to the simulations was generally positive. One common element of feedback was that students found the dynamic representation of molecules and thermodynamic phenomena to be more useful than the static depiction found in books. In fact, Beverly was the only participant who did not state that she found the dynamic molecules and plots useful for helping visualize the system. For example, Alfred said:

"Actually, you know what helps, is actually seeing it moving, I can see which way the path is moving so that kind of guides me along better. Because drawing the path is one thing, but seeing where it starts and ends is also another thing."

David also provided the following comment in response to being asked if he thought the simulations would help people do well in class:

"It definitely wouldn't hold them back. It would, to have a simulation like that, it would have a lot of students including me just understand what's going on. And even if that doesn't help me get a better grade on a test or whatever, at least that tells me what I'm doing, like why am I even bothering with this equation."

Some students also made suggestions for improving the simulations. Frank suggested a button that would give students hints when they are stuck. Henry suggested adding more variety to the systems present in the Reversibility simulation such as including a non-ideal gas or adiabatic systems along with the isothermal ones.

Finally, George had some difficulty understanding what he was asked to do in the Reversibility simulation:

"I guess I took the question as, I wasn't really aware that was a block in the beginning. And I thought it asked me to choose a value of blocks that work them, by a block, and put them on to the simulation. Other than that I think it's great."

Essentially, he did not understand that to place the block on the piston, he had to physically click and drag the block. George's example reinforces the importance of using precise wording when providing instructions to prevent any confusion that may arise from differing interpretations.

SUMMARY

This study examined student engagement and feedback from eight participants using two different Interactive Virtual Laboratories to learn threshold concepts. Student approaches to interacting with and completing the simulations can be roughly divided into two groups: concept-based and equation-based. Students who used a concept-based approach on the simulations were very successful at understanding and explaining the key threshold concept in both the Pv Work and Reversibility simulations. Students who instead used an equation-based approach were forced into a state of conflict during the conceptual simulation sections, as they realized that they could not successfully engage in the simulations using this approach. Participants who completed the Pv Work simulation with an equation-based approach became cognizant of their lack of conceptual understanding but did not change their approach. However, participants who completed the Reversibility simulation switched to a concept-based approach when presented with increasingly complicated thermodynamic systems. Comparisons between the Pv Work and Reversibility simulations suggest that IVLs are most successful when using a highly scaffolded design along with a series of increasingly complex systems to ease the student into comprehension. Additionally, student feedback to the simulations was largely positive. Students particularly liked how the IVLs provide a visual and dynamic representation of the abstract thermodynamic systems. Some student suggestions for simulation improvements include adding buttons for additional hints and assistance as well as adding more complexity to the systems, such as including non-ideal gases or switching between adiabatic and isothermal systems. The IVLs are available for instructors to use through the A/ChE Concept Warehouse website (<http://cw.edudiv.org/>).

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HANDOUTS WITH GAPS

Richard M. Felder
Rebecca Brent

When you’ve given enough teaching workshops, you start to anticipate certain questions from the participants. In our workshops, for example, as soon as we mention active learning we can count on someone immediately asking how they’re supposed to cover their syllabi if they start filling their lectures with activities.

When we get that question we trot out one or more of three responses. First, the point of teaching is not coverage, but learning. If you cover something and most students don’t learn it, you haven’t taught it. Second, you can have a major impact on learning by including just a couple of minutes of activity in a 50-minute class, which won’t do irreparable harm to your syllabus coverage. Our third response not only preserves your syllabus but allows you to extend it while doing all the active learning you want to. This response does double duty, since it also answers another FAQ: How can I catch up with my class schedule when I fall a week or more behind, as I invariably do in every course I teach?

Here’s how: use handouts with gaps. Put your lecture notes in class handouts or (if you have the complete set of notes) a coursepack, but not the complete notes. Show straightforward parts of the lecture material—definitions, facts, simple math, diagrams, and plots—with interspersed blank spaces (gaps) for students to insert answers to questions, missing parts of problem solutions and derivations, and visuals such as molecular, physical, and biological structures, free-body and circuit diagrams, and process and algorithm flow charts. In class, give students brief periods of time to read the straightforward parts themselves, and use lecturing or active learning to fill in the gaps.

An illustrative page from a handout for an introductory fluid dynamics course is shown at <www.ncsu.edu/felder-public/Columns/FDHandout.pdf>. (We suggest you bring it up now—it will make what follows more comprehensible.) If you were conducting this particular class session, you would begin by asking the students to open their handout or coursepack to page 35 and read the top half of the page, which contains a simple description of fluid flowing in a pipe. You would stop them when you think they’ve had enough time and ask if they have any questions (they generally don’t). You’ve just saved a chunk of time relative to a traditional lecture, since the students can read much faster than you can speak and write.

Next comes a problem statement (“Derive an expression for the mass flow rate…” ) and a gap for the solution. There are three different things you can do at that point.

1. Lecture on the material that goes in the gap.

Tell the students that what they just read is straightforward but that derivation is tricky and students often have trouble with it, and then go through it as you would in a traditional lecture. The idea is to focus most of the class time on material the students really need help with, as opposed to spending a lot of it on definitions and simple calculations that the students can quickly read through on their own.

2. Use active learning to get students to fill in the gap.

A more effective strategy is to tell the students to get into groups of two or three and give them a short time to go as far as they can with the derivation, then stop them and call randomly on several to report on the steps they carried out.

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Write correct responses on the board so everyone in the class gets them. Some students will work out the derivation and so will own it, because they did it themselves rather than just watching you do it and imagining that they understood all of it. (Few students understand complex material when they just listen passively to a lecture on it.) Others will try but won’t get the solution in the allotted time. As it goes up on the board, though, most of those students will pay careful attention, ask questions if necessary, and understand it by the end of that class session.

3. Leave filling in the gap as an exercise for the students to complete outside of class.

Tell the students that you don’t plan on going over a gap in class, but they should make sure to find out what goes in it before the next test. They can work with each other and ask about it in class or in your office if they can’t figure it out themselves. If you fall behind your lecture schedule, increase your use of this option for easier and less important material.

Rich used handouts with gaps for the last 20 years of his active teaching career. Even though he also used active learning extensively, his syllabi actually got longer than they were when he felt it necessary to say every word and draw every diagram and work through every step of every derivation and problem solution in class. The brief struggles the students had in class followed by immediate feedback saved many of them from hours of wrestling with similar exercises in the homework.

Research has confirmed that handouts with gaps have a powerful impact on learning and performance on assignments and tests. In several studies, students who got incomplete notes on course material earned higher exam grades, higher course grades, and higher marks on conceptual questions than students who had complete notes.[2-4]

Faculty members sometimes raise objections to the concept of handouts with gaps.

**Objection 1:** Students learn a lot by taking notes in class. If I give them most of the lecture notes in handouts, they won’t bother taking their own notes and will learn less.

**Response:** The research says otherwise. When students are busy copying definitions, tables, figures, equations, and simple mathematical operations, they can’t simultaneously pay full attention to explanations in the lecture, and they consequently miss important material.[5]

**Objection 2:** Putting my complete lecture notes into handouts with gaps will take much more of my time than I can afford to spend.

**Response:** What takes huge amounts of time is preparing the notes in the first place. Once you have them, it doesn’t take much additional time to add gaps by pasting physical or electronic blank rectangles over responses to questions, calculations, and drawings you want students to complete.

**Objection 3:** My students think I’m obliged to tell them everything they need to know. They’ll complain if I leave gaps in the course handouts, and they may completely revolt if I make them fill the gaps in themselves.

**Response:** Complete revolt over gaps is unlikely but you can count on some students complaining about them, just as you can count on complaints about active learning. Fortunately, you can take steps to defuse or eliminate student resistance to those and all other learner-centered teaching methods.[6] Taking some of those steps—including offering to share the research showing that the method leads to higher grades—should keep the pushback at a manageable level long enough for most students to realize that what you’re doing is in their best interests. At that point the complaints generally stop.

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Chemical Engineering at . . .

Yangon Technological University

“This is Burma, and it will be quite unlike any land you know about.”
—Rudyard Kipling, describing his 1889 visit to Burma

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Yangon Technological University (YTU) is the premier engineering school in Myanmar, formerly known as Burma. It is Myanmar’s oldest engineering program, and its students currently have the highest entrance exam scores of any university in the country. The YTU Department of Chemical Engineering has existed since 1958. Myanmar itself is a country with a long history of engineering excellence, which can be seen in its many beautiful temples that date back over a thousand years. It is the 25th most populous country in the world, with more than 50 million people, and it is situated between some of the fastest-growing economies in the world (China, India, and Thailand). The university is located in Yangon, Myanmar’s largest city and its former capital.

But, paraphrasing Kipling: This is Myanmar, and the Department of Chemical Engineering here is quite unlike any department you know about.

Based on the context described in the paragraph above, the reader would probably be surprised to find out that:

(i) There are only 534 undergraduates currently at YTU, including only 26 chemical engineering undergraduates, and all of these students are in their first two years of study.

(ii) Seven of the nine full-time chemical engineering faculty members are under the age of 35, and all seven received their degrees from the same university.

(iii) Women constitute 70% of the Department of Chemical Engineering (at all levels—faculty, graduate, and undergraduate).
The campus environment is unique, both inside and outside the classroom: computer methods (e.g., spreadsheets, process simulators) are not used in the curriculum; students will kneel and bow to faculty with their face touching the ground, in a show of respect; lines of monks in crimson robes are welcomed daily on campus for food donations.

YTU has had four different names in its 53-year history.

To understand these unusual circumstances, one needs to consider the recent political history of Myanmar and its impact on the university system.

AN INTERWOVEN HISTORY OF MYANMAR AND YTU

The British colonized Burma in the 19th century and Burma was ruled as a British colony from 1885 until 1948. The capital of Burma was Rangoon, the largest city in the country. There have been colleges in Burma since the early times of British rule, and several of these colleges merged to form Rangoon University in 1920. An engineering department was formed at Rangoon University in 1924. An engineering society, the Association of Engineers of Burma, began in the 1920s.

In late 1946, General Aung San, the father of Burmese independence, became Deputy Chairman of the Executive Council of Burma, a transitional government. But on July 19, 1947, political rivals assassinated General Aung San and several cabinet members. On Jan. 4, 1948, Burma achieved independence from Britain, and became a democracy based on the parliamentary system. This period saw the formation of the Department of Chemical Engineering within the engineering program at Rangoon University in 1958. Then, in 1961, the engineering program from Rangoon University moved to a new campus and was named the Burma Institute of Technology.

In 1962, General Ne Win launched a military coup and established a nominally socialist military government that sought to follow the “Burmesse Way to Socialism.” The government enacted a law banning all associations in 1963, and so the Association of Engineers in Burma was abolished. In 1964, the Burma Institute of Technology became an independent university, and was renamed the Rangoon Institute of Technology.

There were sporadic protests against military rule during the General Ne Win years and these were almost always violently suppressed. In 1974, the military violently suppressed anti-government protests at the funeral of U Thant, the former United Nations Secretary General. In 1987, currency devaluation wiped out many people’s savings and triggered nationwide anti-government riots. In 1988, large demonstrations against the government occurred all over the country; these had originated with students from the Rangoon Institute of Technology. Thousands of people were killed when the government suppressed the protests and all universities in Myanmar were closed for two years.

The State Law and Order Restoration Council (SLORC) was formed in 1989 by the military to govern the country. It immediately declared martial law, arresting thousands of people including many advocates of democracy and human rights. The National League for Democracy (NLD) leader Aung San Suu Kyi, the daughter of General Aung San, was put under house arrest. Furthermore, the government renamed Burma as Myanmar and Rangoon as Yangon; thus when it re-opened in 1990 the Rangoon Institute of Technology became the Yangon Institute of Technology. In protest of the regime, the United States did not recognize the names Myanmar and Yangon, and did not have an Ambassador to Burma from 1990-2012.

As of mid-1996 the situation for chemical engineering education in Myanmar was as follows. Two universities, Yangon Institute of Technology and Mandalay Institute of Technology (founded 1991), offered undergraduate and master degrees in chemical engineering. There were no Ph.D. programs in chemical engineering in the country. In addition, there were several government technical institutes that offered two-year diploma programs for training technicians in chemical engineering.

Standing outside the Shwedagon Pagoda—the glittering Buddhist monument in the heart of Yangon—are YTU faculty members Dr. Su Su Hlaing and Dr. April Htet (both on the left) along with two CWRU students.
engineering-related areas (e.g., plastic, rubber, and food technology); these diploma programs are similar to associates degree programs at community colleges in the United States.

But the situation changed drastically in 1996. Aung San Suu Kyi, who had won the Nobel Peace Prize in 1991 while under house arrest, was released in 1995. As she attended her first NLD congress since her release in 1996, the government arrested more than 200 delegates on their way to the party congress. These arrests prompted student demonstrations in Yangon, again originating with students from Yangon Institute of Technology and Yangon University; many of these students were arrested. At this time the United States and the European Union imposed economic sanctions, banning imports to Myanmar and investment within Myanmar. The government responded to the student protests by closing all the universities and colleges in the country. All universities and colleges remained closed for the 1996–97 academic year.

Around this time a new government ministry, the Ministry of Science and Technology, was formed. The Yangon Institute of Technology was transferred from the Ministry of Education to the newly formed Ministry of Science and Technology, and renamed as the Yangon Technological University (YTU). Two initiatives began at YTU. First, a Ph.D. program was started at YTU in 1997. Second, a “special program,” which was tightly controlled and had a military-like character, started at YTU in 1998. This special program was limited to small numbers of students (50–150 incoming students per year, in all engineering fields), who were designated as government officers and received a salary. The special program required students to live on campus, included daily physical exercise classes led by retired military officers, and required the students to sign contracts to serve in the Ministry of Science and Technology after graduation—four years for a bachelor’s degree, six years for a master’s degree, and 15 years for a doctoral degree.

The “special program” at YTU was limited to a very small number of undergraduates. Meanwhile, the regular engineering programs at the universities in Myanmar remained closed for three years. Students who completed several years of study when the universities closed in 1996 had to wait three years to continue their studies. In 1999, universities and colleges reopened, but not in the usual locations—the regular students had to attend classes on remote campuses far from the cities (where they would not be able to demonstrate against the government). The students from the Yangon Institute of Technology took classes on a campus in Pyay, a remote location 250 km from Yangon. These students were still referred to as YTU students, and were taught by YTU faculty, but at a location far from Yangon. The YTU faculty had to travel between Yangon and Pyay—spending about a week at a time at each—in order to teach both the graduate students in Yangon and the undergraduate students in Pyay. But these initiatives didn’t last long. The special program at YTU closed in 1999, and all students were transferred to the special program at Mandalay Technological University (MTU), which in turn stopped accepting new students in 2001. The regular undergraduate program at YTU (which was really situated in Pyay) closed in 2001.

To replace the closed undergraduate programs at YTU and MTU, the Ministry of Science and Technology converted the diploma-level government technical institutes for training technicians into bachelor’s-level government technical universities for training engineers. The same faculty who had been teaching the diploma courses in fields like plastics technology and food technology, and who held only bachelor’s degrees, were now teaching the undergraduate chemical engineering students. In addition, some new universities were established, including two that had chemical engineering programs.

In the middle of 2012, the situation for chemical engineering education in Myanmar was as follows. There were five undergraduate chemical engineering programs in Myanmar—three at former government technical institutes and two at new universities formed in 2005—and the quality of the education in these programs was not very high. YTU had essentially been closed since 1996, although it maintained a small graduate program during this time. Almost the entire YTU faculty had left the university—a few went to the new universities, but most went to industry or retired. And for the previous 15 years very few chemical engineers in Myanmar had graduated from strong educational programs.

NORMALIZING RELATIONS

But the situation in Myanmar has begun to change, and the country is undergoing a transition from military rule to democracy. Aung San Suu Kyi was released from house arrest in 2010. Free and peaceful elections were held in 2012, and Aung San Suu Kyi and the NLD party won 43 of 45 open seats. The United States began normalizing relations with Myanmar in 2012—most sanctions were lifted, an ambassador was appointed, and President Obama visited the country.

The undergraduate program at YTU re-opened in December 2012. This process is slow and difficult, and will take six years to complete—e.g., there were only first-year students in 2012–13, first- and second-year students in 2013–14, and so on. Almost all of the faculty members at YTU are new hires, because almost all of the previous faculty members had left. The strongest faculty candidates in 2012 were graduates from the “special program” at MTU in the early 2000s that stayed on at MTU for their Ph.D.s—this is the reason that seven of the nine faculty members in the chemical engineering department are younger than 35 and have their Ph.D.s from MTU.

Currently, the Chemical Engineering Department has nine permanent faculty members. Five have Ph.D.s in chemical engineering, two have Ph.D.s in biotechnology, one has an M.E. in chemical engineering, and one has a bachelor’s in industrial chemistry. There are also five visiting professors
and one visiting lecturer who help with teaching. Although retired, former department heads Dr. Maung Maung Win and Dr. Mya Mya Oo still give advice and guidance to the faculty.

**ACADEMIC PROGRAMS**

**Undergraduate program**

The undergraduate program reopened at YTU in 2012 with a new six-year curriculum. Currently there are 26 students in the undergraduate degree program, but by 2018, when all six years of the program become populated, there will be more than 100 undergraduate chemical engineering students (based on the planned enrollment of 20 new students per year).

The first year of the program is at a level similar to high school courses in the United States, which is necessary due to the poor secondary schools in much of Myanmar. The second year is similar to the first year of a college engineering program in the United States, and the students take mathematics, English, and basic science and engineering courses.

In the third to fifth years, students take a fairly typical chemical engineering course of study, including the usual chemical engineering courses, as well as more mathematics, science, and core engineering courses. Students also take humanities courses and English courses. Students are required to take an elective course in chemical technology each semester — topics include food, polymer, pulp and paper, petroleum and petrochemical, renewable energy, nano-technology, and environmental technology. Students also complete industrial practical training at a company site for two weeks during the academic-year breaks; the company that a student is matched with depends on the technical elective courses taken by the student.

The sixth year is all project-based. In the first semester, students do either a research project in the department labs or work with a community in applying engineering to help the community. In the second semester, students do an internship in industry, where they practice processing and design as well as administration, planning, and marketing skills.

**Graduate programs**

The master’s degree typically takes two years to complete — one year of coursework and one year for research. There are currently six students in the master’s program.

The Ph.D. degree program takes three years after completion of the master’s degree. Students take classes and write a research proposal in their first year, and do research in the next two years. The students present their research results every two months to the department, and then defend their thesis in front of the advisory board. There are currently three students in the Ph.D. program.

The Diploma in Food Technology (DFT) program is a one-year course of study after the bachelor’s degree. This program attracts students from a variety of undergraduate majors, and provides the necessary knowledge and technical skill for food technology. Most students in this program are staff from food industries and medical doctors from the Myanmar Food and Drug Administration. There are currently eight students in the DFT program.

**RESEARCH**

The research in the Department of Chemical Engineering at YTU focuses on the unique energy, environmental, and food technology issues that have an impact on Myanmar.

A major YTU project has been to develop biogas facilities to provide electricity for rural villages in Myanmar. Less than 15% of the people in Myanmar have access to electricity, which is the lowest electrification rate of any country in the world outside of Africa; most of those without electricity live in small rural villages far from the electrical grid. The biogas facilities use cow dung as the source for energy (there are many cows in these rural villages). The cow dung is converted to methane in bioreactors, and the methane is used to power generators that provide electricity. Once built, the biogas facilities are operated communally by the villagers. The YTU-led team has built biogas facilities in 183 villages throughout Myanmar, which provide electricity for over 100,000 villagers who were previously without electricity. Prof. Myo Myo Oo has led the biogas project.

Another YTU project addresses providing electricity for villages, small industries, and agriculture sectors (especially rice mills) through gasification of biomass. A down-draft gasifier driving a 20 kw fuel engine was developed at YTU in 2004 with funding from the Ministry of Science and
Laboratories of the Department of Chemical Engineering: processing laboratory and unit operations laboratory.

Technology. The feedstock for this gasifier is wood chips, and more than 20 of these 20 kw gasifier facilities have been installed at rice mills throughout the country. Research is now being carried out to expand the process to use other feedstocks. In particular, rice husk is an abundant biomass in Myanmar. However, when gasification is carried out with rice husks, it is hard to attain a smooth-running condition because of the low heating value, the low bulk density of the rice husk, and ash and tar problems that occur during gasification. Currently, YTU faculty member Myo Min Win and his graduate student carry out research on the catalytic gasification from pelletized rice husk in order to gasify at lower temperatures. This system is intended to overcome the problems that have limited the use of gasification technology with the rice husk feedstock.

Myanmar is facing water pollution problems because there are no relevant environmental protection laws and most industries did not install wastewater treatment facilities (the Ministry of Environmental Conservation and Forestry is currently drafting laws to require such facilities in the near future). YTU faculty members, along with graduate students, are carrying out several research projects on wastewater treatment, with the goal of transferring technologies to industry. Faculty members Nwaynay Hlaing and Lat Lat Tun are conducting research on the anaerobic fermentation of industrial wastewater, and Su Su Hlaing is working on wastewater treatment by adsorption.

HOW YTU DIFFERS FROM U.S. UNIVERSITIES

Due to the isolation of Myanmar from the rest of the world and the long-standing control of the universities by the military government, as well as the unique culture of Myanmar that is closely tied to Buddhism, there are a number of aspects of YTU that are very different from universities in the United States.

Interactions with other countries

YTU has been very isolated from the world outside of Myanmar. As noted, all of the chemical engineering faculty members received their degrees from universities in Myanmar. As of mid-2013, none of the chemical engineering faculty had spent extended periods of time outside of Myanmar, and in their studies they had not interacted with faculty or students from outside of the country. This situation is very different from other places in the world, where significant international exchange in universities is common (in even the poorest countries in Africa many of the faculty have studied outside of their country).

But that’s beginning to change. Visitors from other countries are now coming to YTU to interact with the faculty and students. In 2013, Prof. Daniel Lacks from Case Western Reserve University (CWRU) twice visited on a Fulbright program to work with the faculty at YTU. On his second visit, 13 students from the CWRU Masters of Engineering Management program came to YTU and joined 13 Myanmar participants for the course International Engineering Entrepreneurship—the first U.S. academic course in Myanmar in at least 25 years.

The YTU chemical engineering faculty members are now also spending time at universities in other countries. In late 2013, Lat Lat Tun began a two-year stay at the Korea Institute of Science and Technology (KIST) in South Korea. Nwaynay Hlaing and April Htet spent the Fall 2014 semester as visiting professors at CWRU, where they have been involved in teaching and research. In 2015, four of the chemical engineering faculty members (Hlaing, Htet, Win, Kuang) began carrying out research at various universities in Japan.

Male to female ratio

When looking at the first photo in this article, there is something striking—17 of the 20 YTU members in the picture are women!
The picture shows the group of faculty and students from YTU that interacted with Lacks during his Fulbright program in Myanmar in 2013. This group was not selected to be mostly women, but rather reflects the high female/male ratio characteristic of YTU. This situation contrasts, of course, with the United States where engineering is predominantly male.

The female/male ratio for the chemical engineering faculty is 2:1, which is also the ratio of YTU faculty as a whole. Of the M.E. and Ph.D. students, seven of the nine current students are women. In the DFT program, about 70% of the students are women. One reason for the high female/male ratio relates to the job market. Male students tend to find jobs after their undergraduate degree more easily than female students, and thus more female students pursue graduate degrees (and thus academic careers). The DFT program is mainly populated by female medical and pharmacy students because it will help them obtain a job in the Myanmar Food and Drug Administration. A further reason for the high female/male ratio of faculty is that university faculty members earn low salaries compared with employment in industry, and more men than women feel that the university salary would not be sufficient to support their lifestyles.

In the case of undergraduate students, about 75% of the students in the chemical engineering department are female. YTU admits 50% male and 50% female students overall for the undergraduate program; even though more females than males pass the entrance exams with higher scores, YTU aims to maintain a balanced female/male ratio. However, most male students choose mechanical, mechatronic, or petroleum engineering, leaving chemical engineering to be mostly female.

**Teaching system**

Students at YTU take up to eight courses each semester, including some with labs. For this reason students need to attend classes from 8 a.m. to 4 p.m., with a break for lunch and 10-minute breaks between classes. The student learning occurs mainly in class, and students are not usually required to solve homework problems outside of class. The instruction is very traditional. Classes are lecture-based; students seldom ask questions in the class, and the class is usually silent except for the instructor lecturing. Problems are solved only with paper, pencil, and calculator—there are no computer-based solutions to problems (e.g., using spreadsheets or software like Matlab), and process simulation software is never used because of its lack of availability. In regard to laboratories, teachers prepare lab instructions and students do experiments following these instructions, without many independent contributions. As Myanmar is opening up and the faculty are interacting with colleagues from other countries, the curriculum will become modernized, including the use of computers in solving problems and enriched lab experiences.

**Campus life**

The traditional culture, closely tied to Theravada Buddhism, plays an important role throughout life in Myanmar. The most easily recognized landmark of Myanmar is the Shwedagon Pagoda, the Buddhist holy site in the heart of Yangon. Also, most Myanmar people have spent time as Buddhist monks or nuns (these 1-4 week stints are akin to religious retreats). The unique Myanmar culture pervades campus life at YTU.

**Dress code:** The YTU faculty members are required to follow a dress code based on the traditional Myanmar style. Male faculty members must wear a white shirt and a longyi (a longyi is a wrap-around skirt). Female faculty members must wear a white blouse with a blue longyi (also called Htamein), where the longyi has white waves from the middle to the lower part of the longyi. Students must wear a white shirt, but with either a longyi or trousers.

**Alms for monks:** Every morning around 9 a.m. monks and novices come to the YTU campus and visit the houses on campus and the canteen to accept donations of food. People from each of the houses and from the canteen are waiting to offer food. Rice is placed into the monk’s bowl and fruits and other items are placed into the inverted lid of the bowl. Curries and vegetables are given in separate containers.

**Kadaw ceremonies:** Myanmar Buddhists pay respect to parents, teachers, and elderly relatives in “Kadaw” ceremonies. In the morning, students wear traditional dress and bring small gifts to teachers. The students take off their shoes, kneel in front of the teachers, and bow with their faces touching the ground. Students not only pay respects as a gesture of gratitude, but also ask forgiveness for any wrongful action they might have done. The teachers, even as they accept the Kadaw from students, ask forgiveness in turn for any wrongful action or hurt they themselves might have been guilty of.

**CONCLUSION**

Myanmar’s circumstances have caused its educational system to lag behind that of much of the world, including its neighbors in Southeast Asia. But Myanmar’s recent political changes—in which the military government is transforming to a democratic government—is giving academics hope that the educational system will be reformed. The faculty of the YTU Department of Chemical Engineering is excited and active in renewing its undergraduate program and expanding its research. The department warmly welcomes you to become involved in its reforming process, as well as to enjoy Myanmar’s culture.

**REFERENCES**

Guess My Birthday: Demonstrating the Significance of Significant Figures

On the first day of my course on material and energy balances, we briefly discuss significant figures. At this point in the curriculum, students understand how to determine the correct number of significant figures in calculated values. However, they do not have a tangible understanding of the relationship between significant figures and precision in measurement, and often report calculated values with greater precision than justified. The following 10-minute exercise does not focus on the rules of rounding significant figures, but rather shows how reporting too many significant figures falsely conveys the degree of precision of a measurement. It’s also a fun way to engage students actively in the classroom early in the semester.

I tell the class that I am 40 years old and ask them to determine my birthday. After getting several quizzical looks and a couple of clever remarks, I point out that we generally truncate our ages rather than rounding, and tell them that I am really 40.9 years old. Smiles recognizing an approaching birthday appear, and some students venture to predict, correctly, that my birthday is in September. But that’s as precise as they can get without an outright guess.

When I tell them instead that I am 40.92 years old, some of them get the idea and pull out their calculators and calendars. After talking with classmates, they guess again, and they are close, but still a few days off. And now they’re eager for the next digit.

So I tell them that I am 40.923 years old. Buttons click, voices hum, they “guess,” and they are right!

Now comes discussion time. These questions can be posed and discussed in pairs or groups:

• We were working with a measurement. What was the device used for measurement?
• What is the precision of a calendar? That is, how closely does a calendar measure time?
• Can a calendar alone be more precise than the nearest day?
• With three decimal places, the correct day was determined. What would be implied if I gave more than three decimal places?

The fact that they can always correctly predict a birthday with three decimal places results from the fraction 1/365, which equals 0.00274… . If I gave another digit, it would not change their determination of my birthday, but it would misleadingly report the time of day I was born. That’s the important point of the exercise, as students tend to give answers with too many significant figures. The value I gave them told the nearest day, and any more digits would represent an unwarranted precision. We discuss how this is analogous to reporting too many digits in calculations involving process variables.

There are a couple of caveats to implementing this exercise.

Due to rounding and occasional terminal zeroes, students sometimes get the correct answer with two decimal places, or, though rarely, with one. Try it yourself, and if that is the case, wait a class period to do the exercise. If you used a 366-day leap year in your calculations, remind them of that as they do their calculations. If your birthday is February 29 and it’s not a leap year, you’ll have to choose another day. And then when you tell them leap day is your real birthday, chances are they will not forget it! So far, they haven’t remembered mine.

—CHRISTY WHEELER WEST, UNIVERSITY OF SOUTH ALABAMA
Inclusion of Six Sigma in ChE Curricula

All repetitive activities produce outcomes by which their performance may be assessed. The outcomes of these processes have specifications imposed on them by the customers they serve. This is true of dynamic manufacturing processes, common in chemical engineering, which respond to changes in the inputs after a time lag, or static transactional processes, abundant in commerce, which respond to changes in the inputs instantaneously. The notion of variation in the outcomes of all processes and transactions arises because uncontrollable and unknown causes are always present. Perfection therefore is not in the plan of nature. Minimum variance is that state beyond which further improvement is not possible because the causes responsible for the residual variation are unknown or uncontrollable. Thus, minimum variance in static and dynamic processes is a theoretical standard against which the performance of practical approaches may be assessed. For dynamic processes, it is possible to design minimum variance control laws but doing so dramatically escalates the cost of control and the system becomes extremely sensitive to modeling errors. Operational strategies for complex dynamic processes therefore aim at achieving a good compromise between the speed of response and system stability in the presence of modeling errors. These optimizing strategies go by the name constrained model predictive control (CMPC) which remains the state of the art today.

The foregoing ideas are well-known to chemical engineers. This editorial suggests that minimum variance control has far greater significance. When applied to static processes the minimum variance methodology goes by the name six sigma created at Motorola about the time when CMPC made its debut in the late seventies and early eighties. Six sigma is the static equivalent of CMPC. Over forty percent of US corporations have adopted six sigma. Since static processes and transactions, encountered in virtually every activity of life, vastly outnumber dynamic processes, six sigma should be in the toolkit of every chemical engineering graduate. Six sigma training will make ChE graduates better control engineers, and help them with job prospects and career advancement.

The author taught a senior/graduate-level six sigma elective in the chemical engineering department for several years prior to retirement. He continues to teach the course elsewhere along with an online version of the course. He introduced mandatory six sigma green belt training in the MBA program of the University of Kentucky and has been teaching the course to their MBA students in Athens, Greece for the past nine years.

Chemical engineering departments should require six sigma training of all graduates and the best way to do this is to include it in their curricula at both the senior and graduate levels. The author equates process control and six sigma training to teaching ChE students the wherewithal of how to achieve the best possible performance in diverse endeavors and for this reason six sigma should not be an option. In addition, many campus recruiters will enthusiastically endorse ChE plans to include six sigma training in the ChE curriculum.

There is so much one-to-one correspondence between process control and six sigma concepts that it might be advantageous to combine the two courses into one new four-credit course. Some topics such as Laplace transforms and the solution of differential equations could be shifted from the process control course to the math courses to make room for six sigma concepts. Some process control concepts could also be shifted to a ChE laboratory where software packages such as MATLAB and MAPLE could be used to reinforce process control concepts. Since six sigma heavily relies on statistics, statistics should be a prerequisite for the course. By coordinating with the instructor of statistics, the necessity of spending time on statistical review can be avoided. The use of statistical software (e.g., SPSS or MINITAB) will avoid the drudgery of repetitive computations and help with the pace.

Instructors interested in including six sigma training as a separate course or as part of their process control offering may contact the author (pradeep@sixsigmaquality.com) for a course outline, syllabus, and a set of MINITAB and MAPLE exercises.

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GUEST EDITORIAL

Inclusion of Six Sigma in ChE Curricula

PRADEEP DESHPANDE
University of Louisville (retired)
Presenting:

CEE’s Annual Grad Guide

for 2015-2016

The following pages feature schools that offer graduate education programs in chemical engineering and related fields. By advertising their programs in this annual graduate education issue, and on our website at <http://www.che.ufl.edu/cee/>,

these schools have financially supported CEE’s ability to continue serving the needs of the international community of educators in chemical engineering.

CEE (Chemical Engineering Education) is the premier archival journal for chemical engineering educators.
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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Graduate Education in Chemical and Biomolecular Engineering

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

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- Cheung: Polymerization in Nanostructured Fluids, Supercritical Fluid Processing
- Cong: Localized Corrosion, Environmentally Assisted Cracking, Corrosion Inhibition.
- Elliott: Molecular Simulation, Phase Behavior, Physical Properties, Supercritical Fluids
- Evans: Material Processing and CVD Modeling, Plasma Enhanced Deposition and Crystal Growth Modeling
- Gupta: Corrosion, Microstructure/Processing/Property Relationships, Nanostructured Materials
- Ju: Renewable Bioenergy, Environmental Bioengineering
- Leipzig: Regenerative Medicine, Tissue Engineering, Biomaterials, Stem Cells
- Lillard: Localized Corrosion, Passivity and Oxide Films, Pipeline Corrosion, AC Induced Corrosion Galvanic Interactions, Corrosion in Nuclear Sys.
- Liu: Biointerfaces, Biomaterials, Antifouling Polymers, Biosensors, Tissue Engineering
- Monty: Reaction Engineering, Biomimicry, Microsensors
- Newby: Surface Modification, Biomaterials, Antifouling/Biofilm/Biocorrosion
- Peng: Materials, Catalysis and Reaction Engineering
- Puskas: Biomaterials, Green Polymer Chemistry and Engineering, Biomimetic Processes
- Visco: Thermodynamics, Computer-aided Molecular Design
- Zheng: Computational Biophysics, Biomolecular Interfaces, Biomaterials
- Zhou: Corrosion Protection by Coating Development and Simulation
- Zhu: Advanced Energy and Nanomaterials Environmental Remediation
A dedicated faculty with state of the art facilities, offering graduate research programs leading to M.S. and Ph.D. degrees. The Department is housed in state-of-the-art buildings on UA’s new Engineering and Science Quad.

Research Areas:

- Bioprocess, Biofuels & Biopharmaceutics
- Biomaterials & Biological Nanomaterials
- Cancer Mechanisms, Models & Theranostics
- Catalysis and Reactor Design
- CO₂ Separation & Gas Treating
- Drug Screening, Resistance & Delivery
- Electrochemical Systems
- Electrodeposition & Spintronics
- Fuel Cells & Photovoltaics
- Functionalized Membranes
- Interfacial Transport & Surface Phenomena
- Ionic Liquid-based Materials & Systems
- Magnetic Materials & Nanotechnology
- Metabolic Engineering / Synthetic Biology
- Molecular Simulations & Modeling
- Polymeric Material Synthesis & Design

Faculty:

David Arnold (Purdue)
Yuping Bao (Washington)
Jason Bara (Colorado)
Christopher Brazel, interim head (Purdue)
Arun Gupta (Stanford)
Yonghyun John Kim (UMBC)
Tonya Klein (North Carolina State)
Alan Lane (Massachusetts)
Xiaoguang Margaret Liu (Ohio State)
Qing Peng (North Carolina State)
Shreyas Rao (Ohio State)
Stephen Ritchie (Kentucky)
Ryan Summers (Iowa)
C. Heath Turner (North Carolina State)
John Van Zee (Texas A&M)
Hung-Ta Wang (Florida)
Mark Weaver (Florida)
John Wiest (Wisconsin)

Contact Info:

Director of Graduate Studies
Chemical & Biological Engineering
The University of Alabama
Box 870203
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An equal employment / equal educational opportunity institution
The Chemical and Materials Engineering Department at the University of Alabama Huntsville offers graduate programs leading to an M.S. or a Ph.D. in advanced areas of chemical engineering, materials science and engineering and biotechnology. Our faculty is dedicated to advancing our understanding of problems in mass transfer, fluid mechanics, materials processing, thin films and adhesion, energy conversion and storage, structure of nano-materials, gene expression, bioinformatics and medical diagnostics. Our faculty works closely with several scientists at the Hudson Alpha Institute for Biotechnology located in Huntsville, Alabama offering students an outstanding opportunity to work on understanding the relationship between genes, gene sequences and the disease process. Our faculty is also dedicated to creating and implementing innovative ideas in teaching which include the use of multimedia technologies and open source software for computing and simulation.
STUDY CHEMICAL AND MATERIALS ENGINEERING
AT THE UNIVERSITY OF ALBERTA, CANADA

The Department of Chemical and Materials Engineering at the University of Alberta is part of the Faculty of Engineering, which ranks in size among the top five per cent of over 400 engineering schools in North America, with about 4,000 undergraduate and 1,600 graduate students.

We offer outstanding research facilities including the National Institute for Nanotechnology; Canadian Centre for Clean Coal/Carbon and Mineral Processing Technologies; Canadian Centre for Welding and Joining; and Institute for Oil Sands Innovation. We also offer the only program in Canada dedicated to Engineering Safety and Risk Management.

Our programs are taught by award-winning professors including a Canadian Excellence Research Chair, seven Canadian Research Chairs, seven Natural Sciences and Engineering Research Council Industrial Research Chairs, making up a faculty of approximately 60 members.

With MSc and PhD programs in chemical engineering and materials engineering and specializations in: advanced materials, process control and systems engineering, nano and regenerative medicine, surface and interfacial science, and energy and natural resources.

All full-time graduate students in research programs receive a stipend. Annual research funding for our Department is over $14 million. Externally sponsored funding to support research in the Faculty of Engineering has increased to over $50 million each year—the largest amount of any Faculty of Engineering in Canada.

For more information visit:
www.cme.engineering.ualberta.ca
Graduate Program in the Ralph E. Martin Department of Chemical Engineering

UNIVERSITY OF ARKANSAS

The Ralph E. Martin Department of Chemical Engineering at the University of Arkansas offers graduate programs leading to M.S.ChE 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. Fellowship applications must be received by January 15.

Areas of Research

- Biochemical and Bioprocess Engineering
- Biomedical Engineering
- Chemical Hazards Assessment
- Energy & Environmental Engineering
- Engineering Education
- Materials
- Membranes & Advanced Separations
- Nanotechnology
- Process Design & Systems Engineering
- Sustainability

Faculty

- M.D. Ackerson
- R.E. Babcock
- R.R. Beitle
- E.C. Clausen
- L.F. Greenlee
- J.A. Havens
- J. Herman
- C.N. Hestekin
- J.A. Hestekin
- W.A. Myers
- D.K. Roper
- S.L. Servoss
- T.O. Spicer
- G.J. Thoma
- H.L. Walker
- S.R. Wickramasinghe

For more information, contact Dr. Christa Hestekin, Graduate Coordinator
chesteki@uark.edu • 479-575-4951 • chemical-engineering.uark.edu
CHEMICAL ENGINEERING
AT AUBURN UNIVERSITY

ALTERNATIVE ENERGY & FUELS BIOCHEMICAL ENGINEERING BIOMATERIALS BIOMEDICAL ENGINEERING BIOPROCESSING & BIOENERGY CATALYSIS & REACTION ENGINEERING COMPUTER-AIDED ENGINEERING DRUG DELIVERY ENERGY CONVERSION & STORAGE ENVIRONMENTAL BIOTECHNOLOGY FUEL CELLS GREEN CHEMISTRY MATERIALS MEMS & NEMS MICROFIBROUS MATERIALS NANOTECHNOLOGY POLYMERS PROCESS CONTROL PULP & PAPER SUPERCritical FLUIDS SURFACE & INTERFACIAL SCIENCE SUSTAINABLE ENGINEERING MOLECULAR THERMODYNAMICS

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ROBERT P. CHAMBERS University of California, Berkeley
VIRGINIA A. DAVIS Rice University
ALLAN E. DAVID University of Maryland
STEVE R. DUKE University of Illinois at Urbana-Champaign
MARIO R. EDEN Technical University of Denmark
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
JAMES RADICH University of Notre Dame
CHRISTOPHER B. ROBERTS University of Notre Dame
BRUCE J. TATARCHUK University of Wisconsin
JIN WANG University of Texas at Austin

AUBURN UNIVERSITY offers a challenging graduate curriculum and research program that prepares its PhD and MS graduates for successful careers. Thanks to an exceptional team of educators and researchers, our department remains at the forefront of discovery and innovation. The size and strength of Auburn’s research program provides important advantages for graduate students. Auburn maintains a top ranking in research awards per faculty member, allowing the department to provide excellent fellowships and assistantships and offer cutting-edge research equipment in our laboratories.

During the past decade, Auburn chemical engineering has continued to increase in size and strength, allowing the program to provide distinct opportunities and advantages to its students, and produce innovative research.

FOR MORE INFORMATION
Director of Graduate Recruiting
Department of Chemical Engineering
Auburn, AL 36849-5127
Phone 334.844.4827
Fax 334.844.2063
www.eng.auburn.edu/chen
chemical@eng.auburn.edu

Financial assistance is available to qualified applicants.

Auburn University is an equal opportunity educational institution/employer.
Vancouver is the largest city in Western Canada, ranked the 3rd most livable place in the world*. Vancouver’s natural surroundings offer limitless opportunities for outdoor pursuits throughout the year - hiking, canoeing, mountain biking, skiing and rock climbing. The city hosted the 2010 Olympic and Paralympic Winter Games and is currently aiming to be the world’s Greenest City by 2020.

The University of British Columbia is the largest public university in Western Canada and is ranked among the top 35 institutes in the world by Newsweek magazine, the Times Higher Education Supplement and Shanghai Jiao Tong University rankings.

Faculty

Susan A. Baldwin (Toronto)
Curtis Berlinguette (Texas A&M)
Xiaotao T. Bi (UBC)
Louise Creagh (California, Berkeley)
Peter Englezos (Minnesota)
Xiaotao T. Bi (UBC)
Savvas Hatzikiriakos (McGill)
Charles Haynes (California, Berkeley)
Dhanesh Kannangara (Ottawa)
Ezra Kwok (Alberta)
Anthony Lau (UBC)
C. Jim Lim (UBC)
Mark D. Martinez (UBC)
Maqsid Mohseni (Toronto)
James M. Piret (MIT)
Dusko Posarac (Novi Sad)
Kevin J. Smith (McMaster)
Vladan Prodanovic (UBC)
Fariborz Taghipour (Toronto)
Heather Trajano (California, Riverside)
Anthony Wachs (Grenoble)
David Wilkinson (Ottawa)
Vikram Yadav (MIT)

Professors Emeriti

Bruce D. Bowen (UBC)
Richard Brannon (Saskatchewan)
Norman Epstein (New York)
John R. Grace (Cambridge)
Richard Kerekes (McGill)
Colin Otoman (UBC)
Royantt Petrill (Florida)
A. Paul Watkinson (UBC)

*August 2014, The Economist Intelligence Unit’s Livability Survey

Financial Aid

Students admitted to the graduate programs leading to the MASc, MSc or PhD degrees receive a minimum level of financial support regardless of citizenship:

MASc, MSc $19,000/year
PhD $21,000/year

Teaching assistantships - up to $1,800/year.

All incoming students are considered for Graduate Student Initiative Scholarships of $5,000 and for 4-year Doctoral Fellowship Scholarships of $18,000/year.
The Department of Chemical and Petroleum Engineering at the University of Calgary, Schulich School of Engineering delivers one of the highest calibre graduate engineering programs in the world with specializations in Chemical Engineering, Petroleum Engineering, Energy & Environmental Engineering, and Biomedical Engineering.

- Internationally recognized graduate program leading ground-breaking research with excellent facilities and generous financial support.
- Unique internationally for its high concentration of researchers working in energy relevant disciplines.
- Opportunity to interact with Canadian oil and gas industry on solving real-world problems.
- Ranked as the fifth most livable city in the world.*
- An hour's drive away from the spectacular Rocky Mountains with easy access to Banff.

* Economist Intelligence Unit 2012 rankings

AREAS OF RESEARCH INCLUDE:

- **Chemical:** 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

- **Petroleum:** 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

- **Environmental:** Air pollution control; alternate energy sources; greenhouse gas control & CO2 sequestration; life cycle assessment; petroleum waste management & site remediation; solid waste management; water & wastewater treatment

- **Biomedical:** Cell & tissue engineering; mechanobiology; biopolymers; protein production; blood filtration; microvascular systems; stem cell bioprocess engineering (media & reagent development, bioreactor protocols); medical diagnostics; regenerative medicine
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 (PDP).

For more information visit our website at:

http://chemistry.berkeley.edu/cbe
The Department of Chemical Engineering and Materials Science at UC Davis is home to two top-ranked graduate programs. We are large enough to boast world-renowned faculty and state-of-the-art research facilities, yet small enough to give every graduate student personal attention.

FACULTY

Klaus van Bentheim
David E. Block
Roger B. Boulton
Ricardo H.R. Castro
Jennifer S. Curtis
Stephanie R. Dungan
Naël H. El-Farra
Roland Faller
Bruce C. Gates
Jeff C. Gibeling
Sangtae Kim
Denise M. Krol
Tonya L. Kuhl
Marjorie L. Longo
Subhash Mahajan
Karen A. McDonald
Gregory H. Miller
Adam J. Moule
Alex Navrotsky
Ann E. Orel
Ahmet Palazoglu
Atul N. Parikh
Ronald J. Phillips
Robert L. Powell III
Subhash H. Risbud
William D. Ristenpart
Ron C. Runnebaum
Sabyasachi Sen
Pieter Stroeve
Yayoi Takamura

RESEARCH AREAS

Chemical Engineering  biochemistry • biomaterials • biotechnology • biomedical engineering • catalysis • colloids & surface science • electrochemical properties & devices • fluid mechanics & rheology • interfaces • mathematical modeling • molecular modeling • nanotechnology • polymers • process control • reaction engineering • renewable energy • thermochemistry • transport phenomena

Materials Science  biomaterials • catalysts • ceramics • electronic, electrochemical, magnetic, and optical properties & devices • glasses • interfaces • materials microstructure and processing • mathematical modeling • mechanical properties • metals • microscopy • molecular modeling • nanomaterials • polymers • renewable energy • sintering • structural materials • thermochemistry • thin films

Designated Emphases are available as specializations in Biotechnology, Biophotonics, and Nuclear Science for doctoral students to tailor their research and coursework.

CONTACT
Alisha Bartolomucci
Graduate Coordinator
alb Bartolomucci@ucdavis.edu
(530) 752-7952

DEGREES OFFERED
Chemical Engineering M.S., Ph.D.
Materials Science M.S., M. Engr., Ph.D.

WEBSITE
For more info, please visit:
chms.engineering.ucdavis.edu
FOCUS AREAS

- Biomolecular and Cellular Engineering
- Process Systems Engineering
- Materials Manufacturing

GENERAL THEMES

- Energy and Chemicals
- The Environment
- Health Care

PROGRAMS

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

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

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

CONTACT

Admissions Office
Chemical and Biomolecular Engineering Department
5531 Boelter Hall • UCLA • Los Angeles, CA 90095-1592
Telephone at (310) 825-9063 or visit us at www.chemeng.ucla.edu
The Department of Chemical and Environmental Engineering is at the University of California Riverside and 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:


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.

NRC RANKINGS

The National Research Council's (NRC) data-based assessment of U.S. Research doctorate programs demonstrated the excellence of the Department of Chemical and Environmental Engineering's faculty and the rapid rise in the quality of its graduate program. CEE was ranked in the NRC's top quartile.

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.

RESEARCH FOR A GREENER WORLD

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
Kelley Barsanti (OGI): Chemical characterization of air pollutants and their precursors; mechanistic modeling of aerosols
Philip Christopher (University of Michigan, Ann Arbor): Developing catalytic processes for efficient, environmentally friendly conversion of natural resources (fossil, biomass, and solar) to fuels and commodity chemicals
David Cocker (Caltech): Air quality systems engineering; atmospheric chemistry
Xin Ge (McMaster): Therapeutic antibody; microbial and enzyme engineering
Juchen Guo (University of Maryland, College Park): Composite materials for energy conversion and storage
Robert Haddad (Penn State): Materials Science and Applications of Carbon Nanotubes and Graphene
David Jassby (Duke): Membrane technology; Water and wastewater treatment; Environmental Nanotechnology
David Kisailus (UC Santa Barbara): Biominalization and Bio-mimetics; bio-inspired nanomaterials synthesis for energy storage/conversion/environmental applications
Haizhou Liu (University of Washington): Metal release in drinking water; application of redox chemical processes in water treatment and site remediation; environmental electrochemistry
Ashok Mulchandani (McGill): Bionanotechnology, biosensors, biocatalysis, biophotovoltaics, biomaterials
Nosang Myung (UCLA): Material electrochemistry; MEMS/NEMS; sensors; nanowires; thermoelectric materials
Sharon Walker (Yale): Bacterial and nanoparticle fate and transport as it pertains to water quality.
Ian Wheeldon (Columbia): Protein engineering; Synthetic biology; Biocatalysis; Biofuels
Bryan Wong (MIT): Density functional theory (DFT); computational materials science, light-harvesting nanomaterials; TD-DFT
Jianzhong Wu (UC Berkeley): Molecular theory and modeling; Density functional theory; Biophysics
Charles Wyman (Princeton): Sustainable production of fuels and chemicals through pretreatment, hydrolysis, and dehydration of cellulosic biomass including wood and grasses
Ruoxue Yan (UC Berkeley): Advanced materials for biological and energy applications to address the pressing medical, energy and environmental challenges facing humanity

WEB www.cee.ucr.edu
E-MAIL gradcee@engr.ucr.edu
APPLY https://gradsis.ucr.edu
Award-Winning Faculty

Bradley F. Chmelka
Patrick S. Daugherty
Michael F. Doherty
Glenn H. Fredrickson, NAE
Michael J. Gordon
Song-I Han
Matthew E. Helgeson
Jacob Israelachvili, NAE, NAS, FRS
L. Gary Leal, NAE
Eric McFarland
Samir Mitragotri, NAE
Michelle A. O’Malley
Baron G. Peters
Susannah L. Scott
Rachel Segalman
M. Scott Shell
Todd M. Squires

Research Strengths

Biomaterials and bioengineering
Energy, catalysis, and reaction eng.
Complex fluids and polymers
Electronic and optical materials
Fluids and transport phenomena
Molecular thermodynamics and simulation
Process systems engineering
Surfaces and interfacial phenomena

Interdisciplinary Centers and Programs

California Nanosystems Institute
Center for Bioengineering
Center for Control, Dynamical Systems, and Computation
Center for Polymers and Organic Solids
Complex Fluids Design Consortium
Dow Materials Institute
Institute for Collaborative Biotechnologies
Institute for Energy Efficiency
International Center for Materials Research
Kavli Institute for Theoretical Physics
Materials Research Laboratory
Mitsubishi Chemicals – Center for Advanced Materials
PIRE in Electron Chemistry and Catalysis at Interfaces

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

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

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 or contact chegrads@engineering.ucsb.edu.
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Complex Fluids Engineering/Nanotechnology
Energy Science & Engineering
Environchemical Engineering
Process Systems Engineering

GRADUATE DEGREE PROGRAMS
Doctorate (Ph.D.)
Course Option Master's
Master of Chemical Engineering
Project Option Master's
Master of Science
Master of Science in Colloids, Polymers and Surfaces
The chemical engineering department at the Case School of Engineering, one of the oldest in the country, offers cutting-edge research programs with field-leading faculty and world-class partner institutions. Our labs are tackling today’s toughest engineering challenges in: energy, materials and biological applications.

**Energy and Electrochemical Systems**
- Fuel Cells and Batteries
- Electrochemical Engineering
- Energy Storage
- Electrodeposition

**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**
- Cell and Tissue Engineering
- Transport in Biological Systems
- Biomedical Sensors and Actuators
- Neural Prosthetic Devices

**Faculty in the Department of Chemical and Biomolecular Engineering**
- Rohan N. Akolkar, PhD, Case Western Reserve
- John C. Angus, PhD, University of Michigan
- Hanif Baskaran, PhD, Pennsylvania State University
- Donald L. Feke, PhD, Princeton University
- Daniel J. Lacks, PhD, Harvard University
- Uziel Landau, PhD, UC Berkeley
- Chung-Chiun Liu, PhD, Case Institute of Technology
- J. Adin Mann Jr., PhD, Iowa State University
- Heidi B. Martin, PhD, Case Western Reserve
- Syed Qutubuddin, PhD, Carnegie Mellon University
- R. Mohan Sankaran, PhD, California Institute of Technology
- Robert F. Savinell, PhD, University of Pittsburgh
- Jesse S. Wainright, PhD, Case Western Reserve

For more information about research opportunities, admission and financial support, email chemeng@case.edu or visit engineering.case.edu/eche
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Yuen-Koh Kao
Soon-Jai Khang
Vikram Kuppa
Joo-Youp Lee
Yoonjee Park
Dale Schaefer
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 A.P. Angelopoulos
The Chemical Engineering Program
Department of Biomedical, Chemical & Environmental Engineering
Cincinnati, Ohio 45221
angelopoulos@ucmail.uc.edu

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.
GROVE SCHOOL OF ENGINEERING

MS & PhD Programs in CHEMICAL ENGINEERING

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Elizabeth J. Biddinger
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M. Lane Gilchrist
Ilona Kretzschmar
Charles Maldarelli
Robert Messinger
Jeffrey F. Morris
Vincent Pauchard
David S. Rumschitzki
Carol A. Steiner
Gabriel I. Tardos
Raymond S. Tu

RESEARCH AREAS

Biomaterials and Biotransport
atherogenesis, bio-fluid flow, self-assembled biomaterials

Catalysis
Catalyst design, reaction kinetics, electrocatalysis

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

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

www-chem.cnccny.cuny.edu
gradinfo@che.cnccny.cuny.edu

212 · 650 · 6671
Clemson University is a land grant University on the shores of Lake Hartwell at the foothills of the Blue Ridge Mountains in South Carolina. The world class research, great weather, & recreational activities make Clemson an ideal place to live and learn.

WHY STUDY AT CLEMSON?

World Class Research:
Over $2 Million Per Year in Research Funding
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Award Winning Faculty:
3 - Faculty Winners of CAREER or YIP Awards
1 - Faculty Winner of PECASE Award
4 - Faculty Fellows of Professional Societies
10 - Journal Editorial Boards Faculty Serve On

Entrepreneurial Spirit:
37 - Faculty Patents & IP Disclosures
3 - Startup Companies Formed by Faculty

Reputation:
20 - Ranked 20th among Public Universities
1 - Ranked Alumni Network

Social Atmosphere:
3 - Ranked Third for Happiest Students!
7 - Graduate Student Tailgates Per Football Season!

PHD & MS PROGRAM

The Graduate Program offers the M.S. and Ph.D. degrees in Chemical & Biomolecular Engineering.

Students with a B.S. in Chemistry, Biochemistry, or other Engineering disciplines are invited to apply directly to the Ph.D. program.

FINANCIAL SUPPORT

All Ph.D. students in good academic standing are offered financial support through research and teaching assistantships. Financial support includes a competitive stipend, full tuition remission, and benefits. Outstanding applicants may be eligible for fellowships.

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FACULTY

MARK BLENNER (Columbia) Metabolic Engineering, Synthetic Biology, Protein Engineering, Biocatalysis

DAVID BRUCE (Georgia Tech) Catalysis, Kinetics, Renewable Chemicals, Molecular Modeling

ERIC DAVIS (Drexel) Polymer Membranes, Transport Phenomena, Poromechanics

RACHEL GETMAN (Notre Dame) Computational Catalysis Catalysis in Metal-Organic Frameworks, Catalyst Design

ANTHONY GUISEPPI-ELIE (MIT) Bioelectronics, Biochips, Biosensors, Biomolecular Engineering

DOUGLAS HIRT (Princeton) Polymer Films, Biopolymers, Surface Modification

SCOTT HUSSON (UC Berkeley) Bioseparations, Advanced Separation Materials, Sustainable Water & Energy Production

CHRISTOPHER KITCHENS (Auburn) Green Chemistry & Engineering, Nanomaterials, Nanocomposites

AMOD OGALE (Delaware) Carbon and Polymer Fibers, Films, Composites

MARK ROBERTS (Stanford) Conducting Polymers, Responsive Electrolytes, Electrochemical Systems

SAPNA SARUPRIA (RPI) Molecular Modeling, Statistical Mechanics, Biological Self-Assembly


MARK THIES (Delaware) Separations, Supercritical Processing & Phase Equilibria, Lignin Purification

CENTERS & PROGRAMS

Center for Advanced Engineering Fibers & Films
Center for Bioelectronics, Biosensors, & Biochips
Palmetto Supercomputing Cluster
Water & Energy Consortium

EXCELLENCE IN RESEARCH

Advanced Materials
Biotechnology & Biomolecular Engineering
Catalysis & Biocatalysis
Energy & Water Sustainability
Modeling & Simulation
UNIVERSITY OF COLORADO BOULDER

Educating and Innovating

Chemical and Biological Engineering

We are a world-class department with 27 faculty (including 1 joint with chemistry), 54 postdoctoral fellows and research technicians, 124 graduate students, and more than 700 undergraduate students. Our research program is extremely active, including research centers in biorefining and biofuels, membranes, pharmaceutical biotechnology, and photopolymerization. Our department has many collaborations with nearby federal agencies such as NREL, NIST, NCAR and NOAA. Our department faculty have received national and international awards including the NSF Waterman Award, the AIChE R. H. Wilhelm Award, the AIChE Professional Progress Award, the AIChE Allan P. Colburn Award, the ASEE Curtis W. McGraw Award, and the ASEE Dow Lectureship Award. Our strong graduate program emphasizes the PhD degree and attracts outstanding national and international students. ChBE provides a 12-month stipend and tuition waivers for full-time Ph.D. students.

Research Areas

- Biocatalysis and Surface Science
- Catalysis and Surface Science
- Computational Science and Engineering
- Energy
- Fluids and Flows
- Interfaces and Self-Assembly
- Membranes and Separations
- Nanomaterials & Nanotechnology
- Polymers and Soft Materials
- Protein Engineering and Synthetic Biology
- Biomaterials and Tissue Engineering
- Biosensing
- Biotechnology and Pharmaceuticals
- Materials Science

Award Winning Faculty

K. S. Anseth (Colorado-Boulder)
C. N. Bowman (Purdue)
S. J. Bryant (Colorado-Boulder)
J. N. Cha (California-Santa Barbara)
A. Chatterjee (Minnesota)
D. E. Clough (Colorado-Boulder)
R. H. Davis (Stanford)
J. L. Falconer (Stanford)
J. M. Fox (California-Berkeley)
R. T. Gill (Maryland)
D. L. Gin (CalTech)
A. P. Goodwin (California-Berkeley)
H. Heinz (ZTH - Zurich)
A. Holewinski (Michigan)
C. M. Hrenya (Carnegie Mellon)
J. L. Kaar (Pittsburgh)
M. J. Mahoney (Cornell)
J. W. Medlin (Delaware)
C. B. Musgrave (CalTech)
P. Nagpal (Minnesota)
R. D. Noble (California-Davis)
T. W. Randolph (California-Berkeley)
D. K. Schwartz (Harvard)
M. R. Shirts (Stanford)
J. W. Stansbury (Maryland)
M. P. Stoykovich (Wisconsin-Madison)
A. W. Weimer (Colorado-Boulder)

Research Centers

Research centers are an important part of the graduate and undergraduate research carried out in the department, and significantly increases the interaction between students and industry.

- Colorado Center for Biorefining and Biofuels (C2B2)
- Renewable and Sustainable Energy Institute (RASEI)
- Center for Membrane Applied Science and Technology (MAST)
- BioFrontiers Institute
- Center for Pharmaceutical Biotechnology
- Photopolymerization Center

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For more information, contact
CU-Boulder, Graduate Admissions Committee, Dept. of Chem & Bio Engineering, 596 UCB, Boulder, CO 80309
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CHEMICAL AND BIOLOGICAL ENGINEERING Department

Evolve from its origins as a school of mining founded in 1873, CSM is a unique, highly-focused University dedicated to scholarship and research in earth, energy, and the environment. With approximately 650 total undergraduate and graduate students and $7-8 million in annual research funding, the Chemical and Biological Engineering Department at CSM maintains a high-quality and dynamic program. Research funding sources include federal agencies such as the NSF, DOE, DARPA, ONR, NREL, NIST, NIH as well as multiple industries. Our research areas include:

MATERIAL SCIENCE AND ENGINEERING
- Organic and inorganic membranes (Way, Herring)
- Polymeric materials (Dorgan, D.T. Wu)
- Colloids and complex fluids (Marr, D.T. Wu, N. Wu)
- Electronic materials (Wolden, Agarwal)
- Molecular simulation and modeling (D.T. Wu, Sum, Maupin)

BIOMEDICAL AND BIOPHYSICS RESEARCH
- Microfluidics/Biophotransport (Marr, Neeves)
- Biological membranes (Sum)
- Metabolic engineering (Boyle)
- Drug delivery/Tissue engineering (Knobs, Neeves)
- Biosensors (Cash)

ENERGY RESEARCH
- Catalysts and kinetics (Carreon, Dean, Herring)
- CO₂ capture (Carreon, Way)
- H₂ separation and fuel cell membranes (Way, Herring)
- Natural gas hydrates (Sloan, Koh, Sum)
- Biofuels: Biochemical and thermochemical routes (Herring, Dean, Maupin)

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Research-Active Faculty
- S. Agarwal (UCSB 2003)
- N. Boyle (Purdue 2009)
- M. Carreon (Cincinnati 2003)
- K.J. Cash (UCSB 2010)
- A.M. Dean (Harvard 1971)
- J.R. Dorgan (Berkeley 1991)
- A. Herring (Leeds 1989)
- C.A. Koh (Brunel 1990)
- M.D. Krebs (Case 2010)
- D.W.M. Marr (Stanford 1993)
- C.M. Maupin (Utah 2008)
- R.L. Miller (CSM 1982)
- K.B. Neeves (Cornell 2006)
- A.K. Sum (Delaware 2001)
- J.D. Way (Colorado 1986)
- C.A. Wolden (MIT 1995)
- D.T. Wu (Berkeley 1991)
- N. Wu (Princeton 2008)

For more information contact Deanna Jacobs at 303-273-3720 or djacobs@mines.edu http://chemeng.mines.edu
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Graduate Programs in Chemical Engineering
M.S. and PhD Programs

--- Faculty and Research Areas ---

S. BANTA  Protein & Metabolic Engineering
M. BURKE  Mixed-experimental-and-computational investigations of advanced combustion and energy systems that utilize multiscale modeling, automation, and data sciences
C.J. DURNING  Polymer Physical Chemistry
D. ESPOSITO  Solar & Electrochemical Energy Conversion
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 Molecular Modeling, Thermodynamics & Statistical Mechanics in Biology
V. ORTIZ  Polymer Physics
B. O'SHAUGHNESSY  Sustainability Energy, Carbon Capture & Storage, Particle Technology
V. VENKATASUBRAMANIAN  Electrochemical Engineering

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The Chemical & Biomolecular Engineering Program at UConn provides students with a thorough grounding in fundamental chemical engineering principles while offering opportunities and resources to specialize in a wide variety of focus areas.

Faculty

George Bollas, Ph.D.
Simulation of Energy Processes, Property Models Development

Kelly Burke, Ph.D.
Natural and Synthetic Biomaterials

Daniel Burkey, Ph.D.
Chemical Vapor Deposition, Engineering Pedagogy

C. Barry Carter, D. Phil., Sc.D.
Interfaces and Defects; Ceramics, Materials, TEM, SEM, AFM, Energy

Yongku Cho, Ph.D.
Protein Engineering, Optogenetics, Neuroimaging, Molecular Neurobiology

Douglas Cooper, Ph.D.
Process Modeling and Control

Cato Laurencin, Ph.D., M.D.
Advance Biomaterials, Tissue Engineering, Biodegradable Polymers, Nanotechnology

Yu Lei, Ph.D.
Bio-nanotechnology, Bio-nanosensors, Bio-nanomaterials, Remediation

Anson Ma, Ph.D.
Nanotechnology, Rheology, Emulsions and Foams, Inkjet and 3-D Printing

Radenka Marcic, Ph.D.
Novel Materials for Energy Conversion and Storage, Biosensors, Coatings

Jeffrey McCutcheon, Ph.D.
Desalination, Water Treatment and Reuse, Polymer Electrospinning, Forward Osmosis

William Mustain, Ph.D.
Electrocatalysis, Batteries, Fuel Cells, Electrochemical Synthesis

Mu-Ping Nieh, Ph.D.
Structural Characterization of Soft Materials, Design of Self-Assembled Materials, Biomembranes

Richard Parnas, Ph.D.
Biodiesel Power Generation, PEM Fuel Cells, Polymer Gels, and Filled Polymers

Leslie Shor, Ph.D.
Biotechnology, Microfluidics, Microbial Assay Systems

Ranjani Srivastava, Ph.D.
Systems Biology and Metabolic Engineering

Luyi Sun, Ph.D.
Composite and Polymer Processing, Energy Conversion and Storage

Julia Valla, Ph.D.
Advanced Fuels Processing, Nanomaterials for Catalytic and Adsorption Processes

Kristina Wagstrom, Ph.D.
Atmospheric Chemistry, Air Pollution Modeling

Brian Willis, Ph.D.
Nanotechnology, Thin Films, Atomic Layer Deposition, Chemical Sensors

Research Centers

- Booth Engineering Center for Advanced Technologies
- Center for Clean Energy Engineering
- Center for Environmental Sciences & Engineering
- Institute of Materials Science
Chemical & Biomolecular Engineering at Delaware is ranked, by all metrics, among the top programs in the US, with a world-wide reputation and reach. Building 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, diverse faculty and participate in a vibrant research and educational environment at the University.

24 CBE Faculty with 12 Named Professors

- Maciek R. Antoniewicz
- Antony N. Beris
- Douglas J. Buttrey
- Wilfred Chen
- David W. Colby
- Prasad S. Dhurjati
- Thomas H. Epps, III
- Eric M. Furst
- Arthi Jayaraman
- Feng Jiao
- Michael T. Klein
- April M. Kloxin
- Kelvin H. Lee
- Abraham M. Lenhoff
- Raul L. Lobo
- Babtunde A. Ogunnaike
- E.Terry Papoutsakis
- Christopher J. Roberts
- Stanley I. Sandler
- Millicent O. Sullivan
- Dionisios G. Vlachos
- Norman J. Wagner
- Bingjun Xu
- Yushan Yan

Research Centers & Training Programs

- Delaware Biotechnology Institute (DBI)
- Center for Catalytic Science and Technology (CCST)
- Center for Molecular and Engineering Thermodynamics (CMET)
- The University of Delaware Energy Institute (UDEI)
- Institute of Energy Conservation (IEC)
- Center for Neutron Science (CNS)
- Center for Composite Material (CCM)
- Chemistry-Biology Interface (CBI)
- Sustainable Energy from Solar Hydrogen IGERT Program (IGERT)
- Systems Biology of Cells in Engineered Environments an NSF IGERT Program (SBE2)

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

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FACULTY

CAMERON F. ABRAMS, PhD, University of California, Berkeley
Molecular dynamics in biophysical systems; Receptors for insulin and growth factors, HIV-1 envelope structure and function

NICOLAS J. ALVAREZ, PhD, Carnegie Mellon University
Optical Field Chromatography; Extensional rheology of novel polymers; Interfacial transport phenomena; Water-based lubrication

JASON B. BAXTER, PhD, University of California, Santa Barbara
Solar cells; Semiconductors nanostructures; Ultrasound spectroscopy

RICHARD A. CARRICORD, PhD, University of Minnesota
Biodegradable polymers; Tissue engineering; Transport in polymers

NILE R. DAN, PhD, University of Minnesota
Self assembly in amphiphilic and polymeric systems; Controlled drug release from polymer-based systems; Systems biology and environmental effects

AARON T. FAFARMAN, PhD, Stanford University
Colloidal nanocarriers; Solution-manufactured solar cells; Electrical and spectroscopic characterization of nanomaterials

VIBHA KALRA, PhD, Cornell University
Electrospinning of organic/inorganic hybrid materials; Molecular/mesoscale simulations; Hierarchically-ordered materials for fuel cell electrodes

KENNETH K. L. LAU, PhD, Massachusetts Institute of Technology
Polymer thin films and devices; Solar cells; Nanomaterials

RAJ MUTHAHAASAN, PhD, Drexel University
Conformal sensors for gas detection; Biosensors; Modeling; Dynamics of fluid-solid interactions

GIUSEPPE R. PALMESE, PhD, University of Delaware
Thermoplastic polymers and biomaterials; Composites and interfaces; Processing-structure-property relationships

JOSHUA SNYDER, PhD, John Hopkins University
Electrolysis, Nanoporous Nanostructures; Fuel Cells, Batteries, Water Electrolysis

MASSOUD SOROUSH, PhD, University of Michigan
Fuel cell modeling, control and optimization; Polymerization reaction engineering; Process systems engineering

MAUREEN TANLEY, PhD, University of California, Berkeley
Electrochemical energy storage and conversion; Batteries; Nanoelectrochemistry

CHARLES WEINBERGER, Emeritus Faculty

STEVEN P. WRENN, PhD, University of Delaware
Ultrasound-triggered drug delivery; Biophysical colloids and membranes; Nanomaterials and graphene-based materials

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The department has 21 faculty members engaged in graduate research and teaching, with interests spanning a wide range of topics including bioengineering, nanotechnology, advanced materials processing and surface and interfacial phenomena. This diversity of interests is reflected in the types of graduate courses available at both the department and the college.

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J.E. Whittow, Ph.D.
M.E. Pozo de Fernandez, Ph.D.
J.R. Brenner, Ph.D.
V. Kishore, Ph.D.
J.C. Mbab, Ph.D.

Research Interests
Spacecraft Technology
Alternative Energy Sources
Materials Science
Membrane Technology
Biomaterials
Tissue Engineering
Nanotechnology

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At the University of Illinois at Urbana-Champaign, our researchers are leaders in catalysis and surface chemistry, biological and biochemical engineering, and soft materials and complex fluids. Faculty and students conduct experimental and computational research in state-of-the-art laboratories and research centers. Graduate students are part of an innovative, interdisciplinary environment and participate in opportunities such as the annual graduate research symposium. Our alumni include legendary engineering scholars and leaders in academia and industry.

The department offers a graduate program leading to a doctoral degree. LEARN MORE AT CHBE.ILLINOIS.EDU

DISTINGUISHED ILLINOIS FACULTY AND THEIR RESEARCH INTERESTS

Rohit Bhargava (Biomedical Image Processing)
Ying Diao (Interfacial Phenomenon, Molecular Assembly for Energy and Healthcare)
Andrew L. Ferguson (Materials Science, Molecular Simulation, Bioinformatics)
David W. Flaherty (Catalysis, Surface Science and Materials Synthesis)
Damien S. Guironnet (Polymer Synthesis, Organometallic Chemistry and Catalysis)
William S. Hammack (Public Outreach and Engineering Literacy)
Brendan A. Harley (Biomaterials and Tissue Engineering)
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Paul J.A. Kenis (Microchemical Systems, Microreactors, Microfuel Cells and Microfluidics)
Hyun Joon Kong (Design of Bioinspired Materials, Stem Cell Niche, and Tissue Engineering)
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Christopher V. Rao (Computational Biology and Cellular Engineering)
Simon A. Rogers (Colloidal Suspensions, Polymers, and Complex Fluids)
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)
Diwakar Shukla (Molecular Engineering, Molecular Modeling and Simulations, Biophysics)
Charles E. Sing (Theoretical Polymer Physics, Statistical Mechanics, and Computer Simulation)
Hong Yang (Nanomaterials for Energy and Biotechnology, Electrocatalysis)
Hulmin Zhao (Molecular Bioengineering and Biotechnology)
ChBE at Illinois Tech (IIT) in Chicago
ChBE at IIT is one of the oldest chemical engineering programs in the country—and we’re also among the most innovative. We offer rigorous academic and research programs in areas of significant relevance to society and industry. Our students benefit from state-of-the-art facilities and internationally recognized faculty—all just minutes from downtown Chicago.

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- **Advanced Materials**
  - Particle Technology
  - Fluidization
  - Transport and Interfacial Phenomena

- **Biological Engineering**
  - Biomaterials
  - Biosensors
  - Tissue Engineering

- **Energy and Sustainability**
  - Bioinformatics
  - Molecular Modeling of Proteins
  - Diabetes
  - Bio-derived Energy
  - Bioremediation
  - Fermentation

- **Systems Engineering**
  - Process Modeling/Monitoring and Control
  - Process System Integration
  - Complex Systems
  - System Theory
  - Nonlinear Dynamics

ChBE at IIT gives you the opportunity to conduct graduate research that strives to meet the present and future needs of cities and communities across the globe. While consistently growing, we continue to strengthen our programs and research areas to enhance our competitiveness.

Faculty
Javad Abbasiyan
John L. Anderson
Hamid Arastoopour
Donald J. Chmielewski
Ali Cinar
Dimitri Gidaspow,
Emeritus
Seok Hoon Hong
Nancy Karuri
Sohail Munir, Chair
Satish J. Parulekar
Victor Perez-Luna
Jai Prakash
Vijay K. Ramani
Jay D. Schieber
J. Robert Selman,
Emeritus
Fouad Teymour
David C. Venerus
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Chemical Engineering Education
Consistently ranked as one of the world’s leading institutions in chemical engineering, the Department of Chemical Engineering at Imperial College London offers exciting opportunities in research and taught postgraduate programmes. The research carried out within the Department covers a very broad spectrum, ranging from technological studies of the behaviour of processes and equipment to techniques for process planning, design and control. This is underpinned by a wide range of specialist research facilities, including a £2 million carbon capture pilot plant – the most sophisticated facility of its kind in the world. The Department has strong links with industrial and commercial organisations, including ABB, BP, Shell, Pfizer, Petronas, GlaxoSmithKline and Unilever, which provide both financial support for bursaries and real world research projects.

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THE DEPARTMENT OF CHEMICAL AND BIOLOGICAL ENGINEERING offers excellent graduate research and education programs in areas important to today’s national and global economies: energy sciences, biorenewables and renewable energy, healthcare, and big data. Our research crosses traditional and disciplinary lines to provide exceptional opportunities to graduate students. Our diverse faculty are leaders in their fields and have received national and international recognition for their research and education.

Our laboratories are state of the art. Recently a $1.75 million project was completed to renovate lab space in Sweeney Hall, home of the chemical engineering program. The Biorenewables Research Laboratory opened in 2010 and is home to one of the world’s top interdisciplinary, systems-level research programs in biorenewables. In addition, the U.S. DOE Ames Laboratory, the NSF Engineering Research Center for Biorenewable Chemicals, the Plant Sciences Institute, the Office of Biotechnology, and the Bioeconomy Institute offer graduate students wonderful opportunities for research and education.

The department offers MEng, MS, and PhD degrees in chemical engineering. We offer full financial support with tuition coverage and competitive stipends to all our PhD students. The department also offers several competitive scholarships to outstanding graduate students.

Iowa State University is located in Ames, Iowa, which was named the No. 2 Best College Town in the U.S. in 2012 by the American Institute for Economic Research.

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Graduate programs in ChemBE at JHU are cutting edge and interdisciplinary. In addition to our Doctoral program, we offer both a research and a course-based Master’s program with an emphasis on Nano & Bioengineering. Doctoral students in good academic standing receive financial support via teaching and research assistantships. Graduate degrees in Chemical and Biomolecular Engineering from Johns Hopkins University will prepare you for successful careers and lifelong learning.

Research Areas
MATERIALS BY DESIGN
MICRO AND NANOTECHNOLOGY
ALTERNATIVE ENERGY AND SUSTAINABILITY
BIOMOLECULAR DESIGN AND ENGINEERING
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Our department strives to be a leader in research and education in the field of Chemical and Biomolecular Engineering. We challenge our students with a rigorous curriculum containing elements of biology, physics, chemistry, and advanced mathematical and computational methods.

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The Art of Science

Background image: A microscopic image of a material in the lungs that aids in respiration captured while it is under stress earned first place for Investigator Prajna Dhar’s research group in the Biophysical Society’s Art of Science Image Contest.

Chemical & Petroleum Engineering at
THE UNIVERSITY OF KANSAS

RESEARCH AREAS

Alternative Energy
biocatalysts, biorefining, fuel cells, batteries, electrochemical reactors and processing

Green Catalysis and Reaction Engineering
ionic liquids, enzyme catalysis, nanocatalysis, process intensification, plasma catalysis, supercritical fluids

Biomedical Engineering
biomolecular product design, biomimetic materials, controlled drug delivery, molecular and tissue engineering, nanomedicine

Improved Hydrocarbon Recovery and Reservoir Engineering
chemical flooding, CO₂ sequestration, nanotechnology, flow assurance, unconventional resources

RESEARCH CENTERS

Bioengineering Research Center (BERC)
Center for Environmentally Beneficial Catalysis (CEBC)
Tertiary Oil Recovery Program (TORP)

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M.S. Petroleum Engineering
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- First principles modeling of catalysts and integrated kinetic models.
- Production of chemicals and fuels from biomass.
- Nanoparticle catalysts and in situ single molecule spectroscopy.
- Biological interfaces for sensing applications.
- Environmental applications of ionic liquids.
- Growth of semiconductor crystals for sensing, light emission and power electronics.
- Nanocarbons for high-energy density lithium ion batteries and chemical sensing.

Professional development opportunities include —
- Developing innovative technologies and processes using state-of-the-art equipment.
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- Networking with associates and collaborators by giving presentations at national and international conferences, and publishing studies on their work in prestigious journals.

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Department of Chemical Engineering
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• Energy Resources and Alternative Energy
• Environmental Engineering
• Interfacial Engineering
• Materials Synthesis • Nanomaterials
• Polymers and Membranes
• Supercritical Fluids Technology

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 interactions with researchers in Agriculture, Chemistry, Medicine and Pharmacy.

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Director of Graduate Studies • Department of Chemical and Materials Engineering • 177 F. Paul Anderson Tower • University of Kentucky • Lexington, KY 40506-0046 • Phone: 859.257.4956
Synergistic, interdisciplinary research in...

- Biomolecular Engineering
- Chemical Energy Engineering
- Catalytic Science & Reaction Engineering
- Environmental Engineering
- Interfacial Transport • Materials Synthesis
- Characterization & Processing • Microelectronics
- Processing • Polymer Science & Engineering • Process Modeling & Control
- Two-Phase Flow & Heat Transfer

**FACULTY**

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<tr>
<th>Name</th>
<th>Affiliation</th>
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<tr>
<td>Jonas Baltrusaitis</td>
<td>Univ. of Iowa</td>
<td>heterogeneous and environmental catalysis • shale gas and biomass conversion</td>
</tr>
<tr>
<td>Bryan W. Berger</td>
<td>Univ. of Delaware</td>
<td>membrane biophysics • protein engineering • surfactant science • signal transduction</td>
</tr>
<tr>
<td>Angela C. Brown</td>
<td>Drexel University</td>
<td>biological colloids • lipid-protein interactions • membrane biophysics • microbial pathogenesis</td>
</tr>
<tr>
<td>Javier Buceta</td>
<td>University of Madrid</td>
<td>cell/tissue biomechanics colloids • systems biology • biological stochasticity • multicellular systems modeling</td>
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<tr>
<td>Hugo S. Caram</td>
<td>Univ. of Minnesota</td>
<td>high temperature processes and materials • environmental processes • reaction engineering</td>
</tr>
<tr>
<td>Manoj K. Chaudhury</td>
<td>SUNY - Buffalo</td>
<td>thin films • surface chemistry</td>
</tr>
<tr>
<td>Mohamed S. El-Aasser</td>
<td>McGill Univ.</td>
<td>polymer colloids and films • emulsion copolymerization • polymer synthesis and characterization</td>
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<tr>
<td>James F. Gilchrist</td>
<td>Northwestern Univ.</td>
<td>particle self-organization • mixing • microfluidics, rheology</td>
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<tr>
<td>Vincent Grassi</td>
<td>Lehigh University process systems engineering</td>
<td>microporous materials characterization</td>
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<tr>
<td>Lori Herz</td>
<td>Rutgers University</td>
<td>cell culture and fermentation • pharmaceutical process development and manufacturing</td>
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<tr>
<td>James T. Hsu</td>
<td>Northwestern Univ.</td>
<td>bioseparation • applied recombinant DNA technology</td>
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<tr>
<td>Anand Jagota</td>
<td>Cornell University</td>
<td>biomimetics • mechanics • adhesion • biomolecule-materials interactions</td>
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<tr>
<td>Christopher J. Kiely</td>
<td>Bristol Univ.</td>
<td>catalyst materials • nanoparticle self-assembly • carbonaceous materials • heterogeneous catalysis • environmental catalysis</td>
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<tr>
<td>Mayuresh V. Kothare</td>
<td>Calif. Inst. of Tech.</td>
<td>Process modeling and control • micro-chemical systems • microengineering control • compact medical devices • microengineering</td>
</tr>
<tr>
<td>William L. Luyben</td>
<td>Univ. of Delaware</td>
<td>polymer rheology and rheo-optics • polymer processing and modeling • membrane formation • drug delivery</td>
</tr>
<tr>
<td>Anthony J. McHugh</td>
<td>Univ. of Delaware</td>
<td>polymer rheology and rheo-optics • polymer processing and modeling • membrane formation • drug delivery</td>
</tr>
<tr>
<td>Steven McIntosh</td>
<td>Univ. of Pennsylvania</td>
<td>fuel cells • solid state ionics • heterogeneous catalysis • functional materials • electrochemistry</td>
</tr>
<tr>
<td>Jeetain Mittal</td>
<td>University of Texas-Austin</td>
<td>protein folding • macromolecular crowding • hydrophobic effects • nanoscale transport</td>
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<tr>
<td>Susan F. Perry</td>
<td>Pennsylvania State Univ.</td>
<td>cell adhesion and migration • cellular biomechanics</td>
</tr>
<tr>
<td>Kelly M. Schultz</td>
<td>University of Delaware</td>
<td>polymer rheology and microchemistry • biocompatible hydrogel characterization • three-dimensional cell culture</td>
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<tr>
<td>Arup K. Sengupta</td>
<td>University of Houston</td>
<td>use of adsorbents • ion exchange • reactive polymers • membranes in environmental pollution</td>
</tr>
<tr>
<td>Cesar A. Silebi</td>
<td>Lehigh University separation of colloidal particles • electrolysis • mass transfer</td>
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<tr>
<td>Shivaji Sircar</td>
<td>University of Pennsylvania</td>
<td>adsorption • gas and liquid separation</td>
</tr>
<tr>
<td>Mark A. Snyder</td>
<td>University of Delaware</td>
<td>inorganic nanoparticles and porous thin films • membrane separations • multiscale modeling</td>
</tr>
<tr>
<td>Kemal Tuzla</td>
<td>Istanbul Technical Univ.</td>
<td>heat transfer • two-phase flows • fluidization • thermal energy storage</td>
</tr>
<tr>
<td>Israel E. Wachs</td>
<td>Stanford University</td>
<td>materials characterization • surface chemistry • heterogeneous catalysis • environmental catalysis</td>
</tr>
</tbody>
</table>

For an application and additional information write to:
Graduate Admissions Committee, Co-Chairs: Dr. Jeetain Mittal or Dr. Steven McIntosh
Department of Chemical and Biomolecular Engineering
Lehigh University
111 Research Drive, Bethlehem, PA 18015
Fax: (610) 758-4261 or Email: inchegs@lehigh.edu
www.che.lehigh.edu
WHY CHOOSE ChE AT LSU?

The Cain Department of Chemical Engineering at LSU is a recognized leader in chemical engineering education and is one of the oldest and most productive departments in the nation. The department continues to be prolific in providing the highly trained graduates needed in the chemical and petrochemical production facilities located in the Gulf Coast area. It has a strong reputation due to its proximity and firm ties to one of the world's largest concentrations of chemical, plastics, paper, and refining industries—as well as a long history of graduates assuming leadership positions in these industries and allied fields.

RESEARCH AREAS

- Advanced Computations
- Biochemical Engineering
- Catalysis
- Energy
- Environmental Engineering
- Materials
- Process Systems Engineering
- Separations

CONTACT

Graduate Coordinator
Cain Department of Chemical Engineering
Louisiana State University
Baton Rouge, Louisiana 70803
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E-mail: relandry@lsu.edu

MORE INFORMATION

- www.che.lsu.edu
- facebook.com/lsu.che
- www.eng.lsu.edu
- facebook.com/lsuengineering
- gradlsu.gs.lsu.edu

BREAKING NEW GROUND

The new and renovated engineering complex will include expanded, modern laboratory space for teaching and translational research, a 250 seat auditorium, approximately 110,000 square feet of classrooms, a new student commons area, updated graduate student space, an academic support center, a dedicated capstone project space, and new labs including an interactive “classlab” and a sustainable living laboratory. The renovated facility will be connected to the chemical engineering addition by a continuous atrium, allowing students and visitors to observe teaching and research projects in action.

PROGRAMS AND FINANCIAL AID

The department offers MS (thesis and non-thesis) and PhD programs, with approximately 50 current graduate students. Assistantships range from $17,500–$23,600 and include a full tuition waiver and waiver of non-resident fees.

OUR GRADUATE FACULTY

- M.G. BENTON
  Pressburg Professor / Assc. Professor; PhD, University of Wisconsin
- K.M. DOOLEY
  BASF Professor; PhD, University of Delaware
- J.C. FLAKE
  Affolter Professor; PhD, Georgia Institute of Technology
- G.L. GRIFFIN
  Nusloch Professor; PhD, Princeton University
- F.R. HUNG
  Horton Professor / Assc. Professor; PhD, North Carolina State University
- F.C. KNOPF
  Anding Professor; PhD, Purdue University
- A.T. MELVIN
  Cain Professor / Asst. Professor; PhD, North Carolina State University
- K. NANDAKUMAR
  Cain Chair Professor; PhD, Princeton University
- J.A. ROMAGNOLI
  Cain Chair Professor; PhD, University of Minnesota
- W.A. SHELTON
  Professor; PhD, University of Cincinnati
- J.J. SPIVEY
  Shivers Professor, Eict Professor; PhD, Louisiana State University
- K.T. VALSARAJ
  Vice President for Research and Economic Development
  Roddiey Distinguished Professor, East Professor; PhD, Vanderbilt University
- D.M. WETZEL
  Pliner Professor, Haydel Professor / Assc. Professor; PhD, University of Delaware
- M.J. WORNAT
  Department Chair
  Harvey Professor, Reymond Professor; ScD, Massachusetts Institute of Technology
- Y. XU
  Cain Professor / Asst. Professor; PhD, University of Wisconsin
This well-established graduate program emphasizes the application of basic principles to the solution of modern engineering problems, with new features in engineering management, sustainable and alternative energy, safety, and biochemical engineering.

For information write to

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

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CHEMICAL,
BIOCHEMICAL &
ENVIRONMENTAL
ENGINEERING

APPLY FOR FREE!
The Department of Chemical, Biochemical and Environmental Engineering at UMBC is pleased to offer citizens and permanent residents of the United States and Canada, and students receiving degree from U.S. and Canadian institutions, the opportunity to apply for admission to our Ph.D. program without admission fees. Details are available on our website (www.umbc.edu/cbe).

PROGRAM DESCRIPTION:
Students pursuing graduate degrees in the Department of Chemical, Biochemical and Environmental Engineering are offered a broad range of research opportunities that apply chemical and environmental engineering principles to problems that are important in today's society. Examples of these research opportunities include the development of novel strategies to remove pharmaceuticals from treated wastewater, understanding the fate and transport of toxic organic compounds in the Chesapeake Bay, developing new bioprocess strategies for the rapid production and purification of biopharmaceuticals, and producing new materials and sensors to enable the development of engineered tissues.

DEGREES OFFERED:
M.S. (thesis and non-thesis), Ph.D. Accelerated Bachelor's/Master's Post-Baccalaureate Certificate in Biochemical Regulatory Engineering

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, NASA, 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, K-12 engineering curriculum development, teacher training
BLANEY, LEE, Ph.D., University of Texas at Austin; Water/wastewater treatment, pharmaceuticals and personal care products
CASTELLANOS, MARIAJOSE, Ph.D., Cornell University; Systems biology, engineering education
ENSZER, JOSHUA, Ph.D., University of Notre Dame; Engineering education
FREY, DOUGLAS, Ph.D., University of California, Berkeley; Bioseparations, Chromatography
GHOSH, UPAL, Ph.D., State University of New York at Buffalo; Fate and transport of toxic organic compounds, remediation of sediments
GOOD, THERESA, Ph.D., University of Wisconsin - Madison; Protein aggregation and disease, cellular engineering
HENNIGAN, CHRISTOPHER, Ph.D., Georgia Institute of Technology; Air pollution chemistry, atmospheric aerosols
LEACH, JENNIE, Ph.D., University of Texas at Austin; Biomaterials, 3-D tissue engineering, stem cells
MARTEN, MARK, Ph.D., Purdue University; Cellular engineering, proteomics, bioprocessing
MOREIRA, ANTONIO, Ph.D., University of Pennsylvania; Fermentation, cell culture, regulatory science
RAO, GOVIND, Ph.D., Drexel University; Biosensor development for bioprocessing, environmental and medical applications
REED, BRIAN, Ph.D., State University of New York at Buffalo; Physicochemical processes, sorption of organics and inorganics
ROSS, JULIA, Ph.D., Rice University; Cell adhesion, biofilms, engineering education
WELTY, CLAIRE, Ph.D., M.I.T.; Groundwater flow and transport, urban hydrology

RESEARCH PROFESSORS:
KOSTOV, YORDAN, Ph.D., Bulgarian Academy of Sciences; Low-cost optical sensors, instrumentation development, biomaterials
TOLOSA CROUCHER, LEAH, Ph.D., University of Connecticut, Storrs; Fluorescence based sensors, protein engineering, biomedical diagnostics, molecular switches

RESEARCH ASSOCIATE PROFESSOR:
GE, XUDONG, Ph.D., UMBC; Sensor matrix development, dialysis based sensor

CONTACT:
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Baltimore, MD 21250
410-455-3400
cbegrad@umbc.edu

www.umbc.edu/cbe
EXPERIENCE OUR PROGRAM IN
CHEMICAL ENGINEERING

Amherst is a beautiful New England college town in Western Massachusetts. Set amid farmland and rolling hills, the area offers pleasant living conditions and extensive recreational opportunities. Urban pleasures are easily accessible.

FACULTY:

W. Curtis Conner, Jr. (Johns Hopkins)
Jeffrey M. Davis (Princeton)
Christos Dimitrakopoulos (Columbia)
Wei Fan (Tokyo)
Neil S. Forbes (California, Berkeley)
David M. Ford (Pennsylvania)
Michael A. Henson (California, Santa Barbara)
Friederike Jentoft (Ludwig-Maximilians, Munich)
Jungwoo Lee (Michigan)
Michael F. Malone (Massachusetts, Amherst)
Dimitrios Maroudas (MIT)
Peter A. Monson (London)
T. J. (Lakis) Mountziaris, (Princeton)
Sarah L. Perry (Illinois, Urbana-Champaign)
Shelly R. Peyton (California, Irvine)
Constantine Pozrikidis (Illinois, Urbana-Champaign)
Jessica D. Schiffman (Drexel)
H. Henning Winter (Stuttgart)

Current Ph.D. projects receive support at a level of over $5 million per year through external research grants. Examples of research areas include:

- **Bioengineering:** cellular engineering; metabolic engineering; targeted bacteriolytic cancer therapy; synthesis of small molecules; systems biology; biopolymers; nanostructured materials for clinical diagnostics.

- **Biofuels and Sustainable Energy:** conversion of biomass to fuels and chemicals; catalytic fast pyrolysis of biomass; microkinetics; microwave reaction engineering; biorefining; high-throughput testing; reactor design and optimization; fuel cells; energy engineering.

- **Fluid Mechanics and Transport Phenomena:** biofluid dynamics and blood flow; hydrodynamics of microencapsulation; mechanics of cells, capsules, and suspensions; modeling of microscale flows; hydrodynamic stability and pattern formation; interfacial flows; gas-particle flows.

- **Materials Science and Engineering:** design and characterization of new catalytic materials; nanostructured materials for nanoelectronics, optoelectronics, and photoelectronics; graphene and carbon nanomaterials; synthesis and characterization of microporous and mesoporous materials; colloids and biomaterials; membranes; biopolymers; rheology and phase behavior of associative polymer solutions; polymeric materials processing.

- **Molecular and Multi-scale Modeling & Simulation:** computational quantum chemistry and kinetics; molecular modeling of nanostructured materials; 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 nanostructures; systems-level analysis using stochastic atomistic-scale simulators; modeling and control of biochemical reactors; nonlinear process control theory.

The University of Massachusetts Amherst prohibits discrimination on the basis of race, color, religion, creed, sex, sexual orientation, age, marital status, national origin, disability or handicap, or veteran status, in any aspect of the admission or treatment of students or in employment.
Materials
Polymers
Nanotechnology
Biotechnology
Energy Engineering
Catalysis and Chemical Kinetics
Colloid Science and Separations
Microchemical Systems, Microfluidics
Statistical Mechanics & Molecular Simulation
Biochemical and Biomedical Engineering
Process Systems Engineering
Environmental Engineering
Transport Processes
Thermodynamics

With one of the largest research faculty in the country, the Department of Chemical Engineering at MIT offers programs of research and teaching which span the breadth of chemical engineering with unprecedented depth in fundamentals and applications. The Department offers graduate programs leading to the master’s and doctor’s degrees. Graduate students may also earn a professional master’s degree through the David H. Koch School of Chemical Engineering Practice, a unique internship program that stresses defining and solving industrial problems by applying chemical engineering fundamentals. In collaboration with the Sloan School of Management, the Department also offers a doctoral program in Chemical Engineering Practice, which integrates chemical engineering, research and management.

D. G. Anderson
R. C. Armstrong
P. I. Barton
M. Z. Bazant
D. Blankschtein
R. D. Braatz
F. R. Brushett
A. K. Chakraborty
K. Chung
R. E. Cohen
C. K. Colton
P. S. Doyle
K. K. Gleason
W. H. Green
P. T. Hammond, Head
T. A. Hatton
K. F. Jensen
J. H. Kroll
H. J. Kulik
R. S. Langer
D. A. Lauffenburger
J. C. Love
A. S. Myerson
B. D. Olsen
Y. Román
G. Rutledge
H. D. Sikes
George Stephanopoulos
Greg Stephanopoulos
M. S. Strano
J. W. Swan
W. A. Tisdale
B. L. Trout
P. S. Virk
D. I. C. Wang
K. D. Wittrup

For more information, contact
MIT Chemical Engineering Graduate Office, 66-366
77 Massachusetts Ave., Cambridge, MA 02139-4307
web.mit.edu/cheme/
The department offers M. Eng. and PhD degrees with funding available and top-ups for those who already have funding.

Downtown Montreal, Canada
Montreal is a multilingual metropolis with a population over three million. Often called the world’s second-largest French-speaking city, Montreal also boasts an English-speaking population of over 400,000. McGill itself is an English-language university, though it offers you countless opportunities to explore the French language.

McGill's Arts Building
For more information and graduate program applications:
www.mcgill.ca/chemeng/
Department of Chemical Engineering
McGill University
3610 University St
Montreal, QC H3A 0C5 CANADA
Phone: (514) 398-4494
Fax: (514) 398-6678

D. BERK, (Calgary)
Biological and chemical treatment of wastes, crystallization of fine powders, reaction engineering [dimitrios.berk@mcgill.ca]

S. COULOMBE, Chair (McGill), Gerald Hatch Faculty Fellow
Plasma processing, nanomaterials, transport phenomena, resource recovery from waste [sylvain.coulombe@mcgill.ca]

P.-L. GIRARD-LAURIAULT, (Polytechnique, Montreal)
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J. KOPYSCINSKI, ETH, (Switzerland)
Chemical engineering & catalysis, conversion of coal and biomass to synthetic fuel

R. LEASK, William Dawson Scholar (Toronto)
Biomedical engineering, fluid dynamics, cardiovascular mechanics, pathobiology [richard.leask@mcgill.ca]

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C. MORAES, (Toronto)
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N. TUFENKJI, Canada Research Chair (Yale)
Environmental and biomedical eng., biodhesion and biosensors, bio- and nano-technologies [nathalie.tufenkji@mcgill.ca]

V. YARGEAU, (Sherbrooke)
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Experience the MICHIGAN Difference

Michigan is a world-class university with top-ranked programs. The University is located in Ann Arbor, a city with a unique blend of cultures and activities, which is traditionally rated one of the best cities to live in the country.

Our students have complete access to the University's rich academic and cultural infrastructure, and will have many opportunities to collaborate and learn from faculty and students in the department, college, and university.

Faculty and Program

- 31 faculty with diverse research topics
- 4 National Academy of Engineering members
- 11 faculty with national awards for research and teaching
- 6 textbooks/monographs
- 120 graduate students
- Teaching Fellow Program

Research Areas

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<th>Biofuels</th>
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<td>Cellular Processes</td>
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<td>Complex Fluids</td>
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<td>Computational Chemistry</td>
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<td>Drug Delivery</td>
<td>Sustainable Energy</td>
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<td>Electrochemical Engineering</td>
<td>Systems Biology</td>
</tr>
</tbody>
</table>

Alex Thompson
PhD 2014
Chemical Engineering and Materials Science
Michigan State University

Faculty

Chemical Engineering

Kris Berglund
Daina Briedis
Scott Calabrese Barton
Christina Chan
Bruce Dale
Lawrence Drzal
Martin Hawley
David Hodge
K. Jayaraman
Ilsoon Lee
Carl Lira
Richard Lunt
Dennis Miller
Ramani Narayan
Robert Ofoli
Charles Petty
S. Patrick Walton
Timothy Whitehead
R. Mark Worden

Materials Science

Thomas Bieler
Carl Boehlert
Martin Crimp
Philip Eisenlohr
Tim Hogan
Wei Lai
Andre Lee
Donald Morelli
Yue Qi
K.N. Subramanian

Nanomaterials & Technology

Composite Materials and Structure Center • Smart Materials • Structured Chemicals • Nanoporous Materials • Grain boundary engineering

Energy & Sustainability

Great Lakes Bioenergy Research Center • Thermoelectrics • Photoelectrics • Batteries • Fuel Cells • Hydrogen storage • Biorenewable polymer and chemicals • Biocatalysis

Biotechnology & Medicine

Metabolic Engineering • Systems Biology • Genomics • Proteomics • RNA interference • Bioceramics • Tissue Engineering • Biosensors • Bioelectrics • Biomimetics

428 S. Shaw Ln Rm 2527 Engineering Building • East Lansing, MI 48842 517.355.5135 • grad_rec@egr.msu.edu

chems.msu.edu
The Department of Chemical Engineering and Materials Science at the University of Minnesota-Twin Cities has been renowned for its pioneering scholarly work and for its influence in graduate education for the past half-century. Our department has produced numerous legendary engineering scholars and current leaders in both academia and industry. With its pacesetting research and education program in chemical engineering encompassing reaction engineering, multiphase flow, statistical mechanics, polymer science and bioengineering, our department was the first to foster a far-reaching marriage of the Chemical Engineering and Materials Science programs into an integrated department.

For the past few decades, the chemical engineering program has been consistently ranked as the top graduate program in the country by the National Research Council and other ranking surveys. The department has been thriving on its ability to foster interdisciplinary efforts in research and education; most, if not all of our active faculty members are engaged in intra- or interdepartmental research projects. The extensive collaboration among faculty members in research and education and the high level of co-advising of graduate students and research fellows serves to spark new ideas and foster 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 wide-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.
Dave C. Swalm School of Chemical Engineering
Mississippi State University

R. Mark Bricka  
Associate Professor
Environmental Engineering  
Soil Remediation

Santanu Kundu  
Assistant Professor
Soft Materials  
Sustainable Materials  
Microfluidics

Bill Elmore  
Associate Professor and
Hunter Henry Chair  
Interim Director
Biotechnology / Biofuels  
Engineering Education

Neeraj Rai  
Assistant Professor
Soft Materials  
Sustainable Materials  
Microfluidics

W. Todd French  
Associate Professor
Microbiology  
Biofuels

Hossein Toghiani  
Professor and Thomas B. Nusz Endowed Professor
Energy / Catalysis  
Fuel Cells / Li-ion Batteries  
Nanocomposite Materials  
Process Control

Priscilla Hill  
Associate Professor
Crystallization  
Particulate Processing

Keisha B. Walters  
Associate Professor
Polymeric and Bio-based Materials  
Nanotechnology  
Surface / Interface Engineering

Jason M. Keith  
Professor and Dean  
Earnest W. Deavenport, Jr. Chair
Reaction Engineering  
Engineering Education

Dong Meng  
Assistant Professor
Soft Materials  
Nanotechnology  
Interfacial Phenomena

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CHEMICAL AND BIOCHEMICAL ENGINEERING FACULTY AND RESEARCH INTERESTS

Muthanna Al-Dahhan (Professor and Chair), D.Sc., Washington University, St. Louis
- Multiphase Reaction Engineering; Energy & Environmental Processes; Advanced Measurement & Computational Techniques

Baojun Bai (Associate Professor Joint Appointment with Petroleum Engineering), PhD, New Mexico Institute of Mining
- Enhanced Oil Recovery Target, Conformance Control, Surfactants, Biosurfactants, Carbon Sequestration

Dipak Barua (Assistant Professor), PhD, North Carolina State University
- Computational Systems Biology, Cell Singling Systems

Sutapa Barua (Assistant Professor), PhD, Arizona State University
- Nanoparticles for Uniform Drug Delivery, Early Detection of Cancer Cells, Treatment of Devastating Diseases

Hank Foley (Joint Appointment, University of Missouri-Columbia), PhD, Penn State University
- Catalysis and Reaction Engineering

Daniel Forciniti (Professor), PhD, North Carolina State University
- Bioseparations; Thermodynamics; Statistical Mechanics

Chang-Soo Kim (Associate Professor Joint Appointment with Electrical Engineering & Biological Sciences)
- PhD, Kyungpook National University
- Functional Integration and Structural Integration of Advanced Microsystems, Biosensors

Xinhua Liang (Assistant Professor), PhD, University of Colorado
- Surface Science; Nanostructured Films & Devices; Catalysis & Reaction Engineering; Energy & Environmental Applications

Athanasios I. Liapis (Professor), PhD, ETH-Zurich
- Transport Phenomena; Adsorption; Bioseparations; Chromatography and Electrophoresis; Chemical Reaction Engineering

Christi Patton Luks (Associate Teaching Professor), PhD, University of Tulsa
- Engineering Education Pedagogy, Sustainable Engineering

Douglas K. Ludlow (Professor), PhD, Arizona State University
- Surface Characterization of Adsorbents & Catalysts; Applications of Fractal Geometry to Surface Morphology

Parthasakha Neogi (Professor), PhD, Carnegie-Mellon University
- Interfacial and Transport Phenomena

Joontaek Park (Assistant Professor), PhD, University of Florida
- Dynamics & Rheology of Complex Fluids / Soft Matters

Fateme Rezaei (Assistant Professor), PhD, Monash University – Melbourne, Australia

Ali Rownaghi (Assistant Research Professor), PhD, University Putra - Malaysia
- Sustainable Energy, Catalysis, Separations

Oliver C. Sitton (Associate Professor), PhD, Missouri S&T
- Bioengineering

Joseph D. Smith (Laufier Endowed Energy Chair Professor), PhD, Brigham Young University
- Multiphase Reacting Flows; Catalysis; Dynamic Simulation; Coal/Biomass Gasification

Jee-Ching Wang (Associate Professor), PhD, Penn State University
- Molecular Simulations of Transport in Confined Systems; Molecular Properties of Materials

David Westenberg (Associate Professor Joint Appointment with Biological Sciences), PhD, University of CA - Los Angeles
- Molecular Microbiology, Microbial Diversity, Microbial Physiology

Silviya Petrova Zustiak (Joint Appointment with St. Louis University), PhD, University of Maryland Baltimore County
- Tissue Engineering, Synthetic Biomaterials
Dr. Ryan Anderson  
Research in PEM fuel cells, multiphase systems, and energy storage

Dr. Jennifer Brown  
Application of magnetic resonance methods and rheology to study transport dynamics in soft matter systems

Dr. Connie Chang  
Research opportunities in biophysics, complex fluids, multiphase flows, emulsion-templated materials, microfluidics, high-throughput assaying of viruses and biofilms

Dr. Ross Carlson  
Systems biology, microbial consortia and biofilms with medical, environmental and bioprocess applications

Dr. Christine Foreman  
Research opportunities in carbon transformations, environmental, microbial and biofilm related applications

Dr. Paul Gannon  
Research opportunities include energy conversion systems, high-temperature corrosion and surface engineering

Dr. Robin Gerlach  
Environmental, energy and biofilm technology-related research for chemical, biological, and environmental graduate and undergraduate students

Dr. Jeff Heys  
Research on computational biofluid dynamics, data assimilation, and biotransport

Dr. Stephanie McCalla  
Research opportunities include biomedical engineering with a focus on biomarker separation and detection

Dr. Brent Peyton  
Research opportunities in renewable biofuels, bioremediation, high temperature biotechnology, and Yellowstone thermal pool biodiversity

Dr. Abigail Richards  
Research opportunities in microbes in extreme environments

Dr. Joe Seymour  
Applying magnetic resonance imaging visualization and quantification of transport phenomena and phase transition dynamics in soft matter, including biopolymers, porous media and colloids

Dr. Phil Stewart  
Research on microbial biofilms in industrial and medical systems focusing on integration of biological and transport phenomena

Dr. Stephanie Wettstein  
Research opportunities for graduate students include catalysis for renewable energy and enhanced separations using zeolites

Dr. Jim Wilking  
Research in soft and biological materials
The Department of Chemical Engineering at UNH is located in the recently renovated Kingsbury Hall with state-of-the-art facilities in Biocatalysis, Biomaterials, Biomedical Engineering, Diagnostic Sensors, Electrochemical Engineering, Fuel Cells and Nanomaterials, Interfacial Flows, Molecular Simulations, Surface Chemistry, and Synthetic Biology. We offer PhD, MS, and MEng degrees in Chemical Engineering. All of our doctoral students are fully supported by teaching or research assistantships. UNH is located in Durham, NH 60 miles north of Boston, 14 miles from the Atlantic coast, and is conveniently located near New Hampshire’s lakes and mountains.

Dale P. Barkey
Electrodeposition, Micro- and Nano-Fabrication, Anodizing

Russell T. Carr
Non-linear Dynamics, Blood Rheology, Microfluidics

Nivedita R. Gupta
Computational Fluid Dynamics, Encapsulation, Interfacial Flows

Jeffrey M. Halpern
Diagnostic Sensors, Surface Chemistry, Sensor Development, Electrochemistry

Kyung Jae Jeong
Biomaterials and Surface Chemistry for Tissue Engineering

Xiaowei Teng
Nanomaterials, Fuel Cells, Supercapacitors, Reaction Engineering

Harish Vashisth
Computational Biophysics, Biomolecular Simulations of Proteins and Nucleic Acids

P. T. Vasudevan
Biocatalysis, Biofuels, Bioengineering

Kang Wu
Synthetic Biology, Protein Secretion, Biofuels, Bioremediation

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Programs in Chemical, Biological and Pharmaceutical Engineering

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 that include catalysis related to alternative energy, polymer science and engineering, membrane technology, pharmaceutical engineering, nanotechnology and energetic materials.

The Faculty:

P. Armenante: University of Virginia
B. Baltzis: University of Minnesota
R. Barat: Massachusetts Institute of Technology
S. Basuray: University of Notre Dame
E. Bilgili: Illinois Institute of Technology
R. Dave: Utah State University
E. Dreizin: Odessa University, Ukraine
C. Gogos: Princeton University
D. Hanesian: Cornell University
K. Hyun: University of Missouri-Columbia
B. Khusid: Heat and Mass Transfer Inst., Minsk USSR
H. Kimmel: (Emeritus); City University of New York

N. Loney: New Jersey Institute of Technology
A. Perna: University of Connecticut
R. Pfeffer: (Emeritus); New York University
R. Rosty: New Jersey Institute of Technology
D. Sebastian: Stevens Institute of Technology
L. Simon: Colorado State University
K. Sirkar: University of Illinois-Urbana
R. Tomkins: University of London (UK)
R. Voronov: University of Oklahoma
X. Wang: Virginia Tech
M. Young: Stevens Institute of Technology
X. Xu: Northwestern University

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Faculty and Research Areas

- **Paul K. Andersen**, Associate Professor and Director of Institute for Energy and the Environment (University of California, Berkeley) *Transport Phenomena, Electrochemistry, Environmental Engineering*
- **Catherine E. Brewer**, Assistant Professor (Iowa State University) *Characterization and Engineering of Biochar*
- **Reza Foudazi**, Assistant Professor (Cape Peninsula University of Technology, South Africa) *Porous Polymers; Rheology of Complex Fluids; Physicochemical Properties of Soft Matter; Colloid and Interface Science*
- **Abbas Ghassemi**, Professor (New Mexico State University) *Risk-Based Decision Making, Environmental Studies Pollution Prevention, Energy Efficiency and Advanced Water Treatment; Renewable Energy*
- **Jessica Houston**, Associate Professor and Associate Department Head (Texas A&M University) *Biomedical Engineering, Biophotonics, Flow Cytometry*
- **Hongmei Luo**, Associate Professor (Tulane University) *Electrodeposition, Nanostructured Materials, Metal Oxide, Nitride, Composite Thin Films, Magnetism, Photocatalysts and Photovoltaics*
- **Thomas A. Manz**, Assistant Professor (Purdue University) *computational chemistry study of advanced materials and transition metal catalysts*
- **Martha C. Mitchell**, P.E., Associate Dean of Research (University of Minnesota) *Molecular Modeling of Adsorption in Nanoporous Materials, Thermodynamic Analysis of Aerospace Fuels, Statistical Mechanics*
- **David A. Rockstraw**, P.E., Distinguished Achievement Professor and Head (University of Oklahoma) *Kinetics and Reaction Engineering; Process Design, Economic Analysis, and Simulation; and Intellectual Property.*

For Application and Additional Information

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

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- Environmental & human health toxicity of nanomaterials

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- 3D bioprinted scaffolds for tissue engineering
- Controlled drug delivery for disease treatment

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- Neural engineering

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- Microfluidic diagnostics
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- Multi-scale computational modeling
- Energy conversion

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- Wide bandgap semiconductors
- Interface engineering

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- Drug delivery systems
- National Academy of Engineering Inductee

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- Microfluidic systems
- Electrochemistry
- Sensors

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- 3D bioprinted scaffold for tissue engineering
- Controlled drug delivery for disease treatment

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- Transport through mucosal barriers
- Biomimetic biomaterials for regenerative medicine

Dr. Nasim Annabi, Assistant Professor
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- Functional 3D tissue constructs
- Nanoscale technologies to control cellular behavior

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Chemical and Biological Engineering

Luis A. N. Amaral, Ph.D., Boston University, 1996
Complex systems, computational physics, biological networks

Neda Bagheri, Ph.D.,
University of California, Santa Barbara, 2007
Computational systems biology; dynamical systems and control theory; applications to immunology, cancer, and circadian rhythms

Linda J. Broadbelt, Ph.D., Delaware, 1994
Reaction engineering, kinetics modeling, polymer resource recovery

Wesley R. Burghardt, Ph.D., Stanford, 1990
Polymer science, rheology

Kimberly A. Gray, Ph.D., Johns Hopkins, 1988
Catalysis, treatment technologies, environmental chemistry

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

Eric Masanet, Ph.D.,
University of California-Berkeley, 2004
Multi-scale and techno-economic modeling of energy, resource, and product life-cycle systems

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

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, polymer physics

Keith Tyo, Ph.D.,
Massachusetts Institute of Technology, 2008
Synthetic biology, metabolic engineering, global health delivery

Fengqi You, Ph.D.,
Carnegie Mellon University, 2009
Process systems engineering, sustainable process design, synthesis

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Faculty and Research Areas

Arunav R. Asthagiri, Carnegie Mellon University
- Computational catalysis, modeling surface chemistry

Bhuvik R. Bakshi, MIT
- Sustainability science and engineering

Nicholas A. Brunelli, California Institute of Technology
- Design of catalytic and nanomaterials

Jeffrey J. Chalmers, Cornell University
- Immunomagnetic cell separation, cancer detection, bioengineering

Stuart L. Cooper, Princeton University
- Polymers, ionomers, and polyurethanes/biomaterials

Liang-Shih Fan, West Virginia University
- Process development of advanced combustion and clean energy systems, gas-solids fluidization

Martin Feinberg, Princeton University
- Mathematics of complex chemical systems

Lisa Hall, University of Illinois at Urbana-Champaign
- Theory and simulation of polymeric systems

W.S. Winston Ho, University of Illinois at Urbana-Champaign
- Molecular and chemical membrane separations

Kurt W. Koelling, Princeton University
- Rheology, polymer processing, and microfluidics

Isamu Kusaka, California Institute of Technology
- Statistical mechanics, transport phenomena in nano-scale systems

L. James Lee, University of Minnesota
- Nanobiotechnology and polymers, composites and nanomaterials

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**Faculty Members**

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

- **Steven P. Crossley**
  Ph.D.
  University of Oklahoma, 2009

- **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

- **Liangliang Huang**
  Ph.D.
  North Carolina State University, 2012

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

- **M. Ulii 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

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

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

- **Bin Wang**
  Ph.D.
  École Normale Supérieure de Lyon, France 2010

For more information, e-mail, call, write or fax:
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Biomedical Engineering
- Tissue Engineering

Energy
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- Modeling / Simulation
- Optimization

Systems Engineering
- Separation Processes
- Sustainability/Process Safety

Faculty
- C. Aichele, Ph.D.
- P. Clarke, Ph.D.
- A. Ford Versyp, Ph.D.
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- Liney Arnadottir - U of Washington
- Nick AuYeung - Oregon State
- Joseph Baio - U of Washington
- Michelle Bothwell - Cornell
- Chih-hung Chang - U of Florida
- Mark Dolan - Stanford
- Elain Fu - U of Maryland
- Stacey Harper - U of Nevada
- Greg Herman - U of Hawaii
- Adam Higgins - Georgia Tech
- Goran Jovanovic - Oregon State
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- Greg Rorrer - Michigan State
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- Travis Walker - Stanford
- D. Wildenschild - Tech U Denmark
- Brian Wood - UC Davis
- Alex Yokochi - Texas A&M

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Chemical & Biomolecular Engineering

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Tobias Baumgart Physical chemistry and mechanics of biological membranes, cell/surface interactions
Sue Ann Bidstrup Allen Polymeric and electronic materials, Electronic packaging and interconnection, high performance batteries
Russell J. Composto Polymeric materials science, surface and interface studies
John C. Crocker Single-molecule biophysics, cell mechanics, soft glasses
Scott L. Diamond Protein and gene delivery, mechnano-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, soft matter
Amish J. Patel Biological self-assembly, desalination, solvation in nano-confined geometries, li-ion batteries, nano-structured polymers
Ravi Radhakrishnan Statistical mechanics, quantum chemistry, biomolecular and cellular signaling
Robert A. Rigglemen Molecular modeling, statistical mechanics, and polymer glasses
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

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Mohammad Ataai  
biotechnology, biomolecular engineering

Anna C. Balazs  
theory, computational modeling, polymers, composites

Ipsita Banerjee  
bioengineering, systems biology, regenerative medicine

Eric Beckman  
sustainability, polymers

Andrew Bunger  
hydraulic fracturing, geological engineering

Julie d'Itri  
catalysis, chemical kinetics, characterization

Robert M. Enick  
petroleum engineering, CO₂ solubility, carbon capture, high pressure phase behavior

Susan Fullerton  
polymer, electrolyte, nanoelectronics, transition metal dichalcogenide, graphene, memory

Di Gao  
nanomaterials, surface science

J. Karl Johnson  
computational modeling, nanomaterials, CO₂ capture and reduction, energy storage

John A. Keith  
computational modeling, catalysis, photoelectrochemistry, renewable energy

George E. Klinzing  
pneumatic conveying, dense phase transport, dense phase flow simulations

Prashant N. Kumta  
energy storage, biomaterials

Lei Li  
surface science, ionic liquids, wetting, tribology

Robert S. Parker  
process control, systems medicine, nonlinear dynamical modeling

Jason Shoemaker  
disease modeling, therapy optimization, AI-guided drug discovery

Sachin Velankar  
rheology, polymers, capillarity, colloids

Giannis Mpourmpakis  
computational modeling, catalysis, nanotechnology, renewable energy

Giigt Veser  
catalysis, process intensification, nanomaterials, nanotoxicity

Christopher Wilmer  
computational modeling, data mining, renewable energy, hypothetical materials

Judith C. Yang  
surface science, catalysis, nanomaterials, materials characterization
Princeton University

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

CBE Faculty
Ilhan A. Aksay
Jose L. Avalos
Jay B. Benziger
Clifford P. Brangwynne
Mark P. Brynildsen
Pablo G. Debenedetti
Yannis G. Kevrekidis
Bruce E. Koel
A. James Link
Yueh-Lin (Lynn) Loo
Celeste M. Nelson
Athanassios Z. Panagiotopoulos
Rodney D. Priestley
Robert K. Prud’homme
Richard A. Register (Chair)
William B. Russel
Stanislav Y. Shvartsman
Sankaran Sundaresan

Affiliate Faculty
Ian C. Bourg (Civil and Environmental Engineering)
Emily A. Carter (Mechanical and Aerospace Engineering)
Sabine Petry (Molecular Biology)
George W. Scherer (Civil and Environmental Engineering)
Howard A. Stone (Mechanical and Aerospace Engineering)
Jared E. Toettcher (Molecular Biology)
Claire E. White (Civil and Environmental Engineering)

Please visit our website: www.princeton.edu/cbe

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- Protein and Enzyme Engineering
- Tissue Engineering

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- Organic Photovoltaics

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- Flow in Porous Media
- Granular and Multiphase Flow
- Polymer and Suspension Rheology

Materials: Synthesis, Processing, Structure, Properties
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- Polymers

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- Heterogeneous Catalysis
- Process Control and Operations

Thermodynamics and Statistical Mechanics
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- Glasses
- Kinetic and Nucleation Theory
- Liquid State Theory
- Molecular Simulation

Write to:
Director of Graduate Studies
Chemical & Biological Engineering
Princeton University
Princeton, NJ 08544-5263

or call:
609-258-4619

or email:
cbegrad@princeton.edu
Research by Fundamental Topic Area

- Biochemical and Biomolecular Engineering
- Catalysis and Reaction Engineering
- Fluid Mechanics and Interfacial Phenomena
- Mass Transfer and Separations
- Nanoscale Science and Engineering
- Polymers and Advanced Materials
- Product and Process Systems Engineering
- Thermodynamics, Molecular and Nanoscale Modeling

Research by Application Area

- Biotechnology
- Electronics
- Energy
- Manufacturing
- Pharmaceuticals
- Polymers and Advanced Materials
- Homeland Security

Faculty

- Rakesh Agrawal
- Osman A. Basaran
- Stephen P. Beaudoin
- Bryan W. Boudouris
- James M. Caruthers
- David S. Corti
- Elias I. Franses
- Jeffrey P. Greeley
- Rajamani P. Gounder
- Robert E. Hannemann
- Michael T. Harris
- R. Neal Houze
- Sangtae Kim
- Carl D. Laird
- James D. Litster
- Julie C. Liu
- Enrico N. Martinez
- Jeffrey T. Miller
- John A. Morgan
- Zoltan K. Nagy
- Joseph F. Pekny
- R. Byron Pipes
- Vilas G. Pol
- Doraishwami Ramkrishna
- Gintaras V. Reklaitis
- Fabio H. Ribeiro
- Jeffrey J. Siirola
- Kendall T. Thomson
- Arvind Varma (Head)
- Jeffrey D. Varner
- Nien-Hwa L. Wang
- Phillip C. Wankat
- You-yeon Won
- Chongli Yuan

The School of Chemical Engineering at Purdue University offers Ph.D., M.S. and Professional M.S. Programs.

FOR MORE INFORMATION
765.494.4057
chegrad@ecn.purdue.edu

Graduate Studies
School of Chemical Engineering
460 Stadium Mall Drive
West Lafayette, IN 47907

Apply online at gradapply.purdue.edu/apply/
Chemical and Biological Engineering

Rensselaer Polytechnic Institute

The Howard P. Isermann Department of Chemical and Biological Engineering has delivered a century of excellence in teaching and research. Its graduate programs lead to research-based MS and PhD degrees and to a course-based ME degree. The department also offers joint programs with the School of Management and Technology for an MS in Chemical Engineering and an MBA or MS in Management. Faculty members maintain close ties to industry, owing to their strong records in sponsored research, consulting, and commercial applications.

Rensselaer Polytechnic Institute in Troy, New York, is the oldest technological research university in the United States. Rensselaer is a private university with an enrollment of approximately 7,000 undergraduate and graduate students in engineering, the sciences, information technology, architecture, management, humanities and the arts. Our faculty members include National Science Foundation Presidential Faculty Fellows and members of the National Academy of Engineering and the National Academy of Sciences. Situated on the Hudson River just north of New York’s capital city of Albany, our campus is conveniently located near New York City, Boston, and Montreal. For more information about Rensselaer’s graduate programs, please contact:

Graduate Admissions
Rensselaer Polytechnic Institute
110 8th Street Troy, NY 12180-3590
Phone: 518.276.6216
Email: gradadmissions@rpi.edu
Web: admissions.rpi.edu/graduate

Emeritus Faculty

Henry R. Bungay III
Wastewater treatment, biochemical engineering

Arthur Fontijn
Combustion, high temperature kinetics, gas-phase reactions

William N. Gill
Microelectronics, reverse osmosis, crystal growth, ceramic composites

Howard Littman
Fluid/particle systems, fluidization, spouted beds, pneumatic transport

Peter C. Wayner, Jr.
Heat transfer, interfacial phenomena, porous materials

Faculty and Research Interests

Georges Belfort: Membrane separations, adsorption, biocatalysis, interfacial phenomena
B. Wayne Bequette: Process control, fuel cell systems, biomedical systems
Vidhya Chakrapani: Semiconductor electrochemistry, energy, advanced materials, optical and electronic properties of wide bandgap materials
Cynthia H. Collins: Systems biology, protein engineering, intercellular communication systems, synthetic microbial ecosystems
Steven M. Cramer: Displacement, membrane and preparative chromatography; environmental research
Jonathan S. Dordick: Biochemical engineering, biocatalysis, polymer science, bioseparations
Shekhar Garde: Macromolecular self-assembly, computer simulations, statistical thermodynamics of liquids, hydration phenomena
Ravi Kane: Polymer, biosurfaces, biomaterials, nanomaterials, nanobiotechnology
Pankaj Karande: Drug delivery, combinatorial chemistry, molecular modeling, high throughput screening
Mattheos Koffas: Metabolic engineering, natural products, drug discovery, biofuels
Sangwoo Lee: Polymers, nanoparticles, nanotechnology, self-assembly, symmetries, soft materials, surfactants
Joel L. Plawsky: Electronic and photonic materials, interfacial phenomena, transport phenomena
Sufei Shi: Two-dimensional materials and metamaterials, nanoscale optoelectronics, ultrafast optical and THz spectroscopy, photocurrent microscopy
Peter M. Tessier: Protein-protein interactions, protein self-assembly and aggregation
Patrick T. Underhill: Transport phenomena; multi-scale model development and applications to colloidal, polymer, and biological systems
CHEMICAL AND BIOMOLECULAR ENGINEERING

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 80 graduate students (Fall 2014).
• 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

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, CO2 sequestration, biochar, gas hydrates, enhanced oil recovery, reservoir characterization, and pollution control.

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.

FACULTY

Sibani Lisa Biswal (Stanford, 2004)
Associate Professor

Walter Chapman (Cornell, 1988)
Professor

Kenneth Cox (Illinois, 1979)
Professor in the Practice

Ramon Gonzalez (Univ. of Chile, 2001)
Professor

George Hirasaki (Rice, 1967)
Research Professor

Deepak Nagrath (RPI, 2003)
Assistant Professor

Matteo Pasquali (Minnesota, 2000)
Professor, Chair of Chemistry

Professor

Laura Segatori (UIT Austin, 2005)
Associate Professor

Francisco M. Vargas Lara (Rice, 2009)
Assistant Professor

Rafael Verduzco (Caltech, 2003)
Assistant Professor

Michael Wong (MIT, 2000)
Professor, Chair Chemical and Biomolecular Engineering

Kyrilacos Zygonakis (Minnesota, 1983)
Professor

Scott Wellington (Case Western Reserve, 1972)
Distinguished Faculty Fellow

Laura Segatori (UIT Austin, 2005)
Associate Professor

Francisco M. Vargas Lara (Rice, 2009)
Assistant Professor

Rafael Verduzco (Caltech, 2003)
Assistant Professor

Michael Wong (MIT, 2000)
Professor, Chair Chemical and Biomolecular Engineering

Kyrilacos Zygonakis (Minnesota, 1983)
Professor

Scott Wellington (Case Western Reserve, 1972)
Distinguished Faculty Fellow

JOINT APPOINTMENTS

Pulickel Ajayan (Northwestern, 1989)
Professor

For more information and graduate program applications, write to:
Chair, Graduate Admissions Committee
Chemical and Biomolecular Engineering
Rice University, P.O. Box 1892
Houston, TX 77251 - 1892
www.chbe.rice.edu

Antonios Mikos (Purdue, 1988)
Professor

Peter Rossky (Harvard, 1978)
Professor, Dean of Weiss School of Natural Sciences

Ka-Yiu San (Caltech, 1984)
Professor

Edwin "Ned" Thomas (Cornell, 1974)
Professor, Dean of George R. Brown School of Engineering

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The Chemical Engineering Department at the University of Rochester offers M.S. and Ph.D. programs designed to both challenge and support our students’ learning. Our graduate programs are among the highest ranked in the nation according to a recent NRC survey*. We provide leading edge research opportunities that cut across the boundaries of chemistry, physics, biology and chemical engineering disciplines with emphasis in energy, materials and biotechnology research. For qualified students, we offer competitive teaching and research assistantships and tuition scholarships.

* 2010 National Research Council Report www.nap.edu/rdp/

**Faculty**

**J. JORNE**  
PhD UC Berkeley, 1972  
electrochemical engineering, fuel cells, microelectronics processing, electrophoresis

**H. MUKAIBO**  
PhD Waseda (Japan), 2006  
materials science, bio/nanoscience, bio-analytical chemistry, electrochemistry, energy storage

**C. W. TANG**  
PhD Cornell, 1975  
organic electronic devices, solar cells, flat-panel display technology

**A. SHESTOPALOV**  
PhD Duke, 2009  
unconventional fabrication, patterning techniques, preparation of functional micro and nanostructured devices

**S. H. CHEN**  
PhD Minnesota, 1981  
polymer science, organic materials for photonics and electronics, liquid crystal and electroluminescent displays

**E. H. CHIMOWITZ**  
PhD Connecticut, 1982  
supercritical fluid adsorption, molecular simulation of transport in disordered media, statistical mechanics

**D. BENOIT**  
PhD Colorado, 2006  
rational design, synthesis, characterization, and employment of materials to treat diseases or control cell behavior

**S. D. JACOBS**  
PhD Rochester, 1975  
optics, photonics, and optoelectronics, liquid crystals, magnetorheology

**M. ANTHAMATTEN**  
PhD MIT, 2001  
macromolecular self-assembly, shape memory polymers, vapor deposition, fuel cells

**D. HARDING**  
PhD Cambridge, 1986  
chemical vapor deposition, mechanical and transport properties, advanced aerospace materials

**D. R. HARDING**  
PhD Cambridge, 1989  
supercritical fluid adsorption, molecular simulation of transport in disordered media, statistical mechanics

**Y. SHAPIR**  
PhD Tel Aviv (Israel), 1981  
critical phenomena, transport in disordered media, scaling behavior of growing surfaces

**A. WHITE**  
PhD Washington, 2013  
computer simulation and data informatics design of materials for self-assembly, batteries and biomaterials

**J. H. DAVID WU**  
PhD MIT, 1987  
bone marrow tissue engineering, stem cell and lymphocyte cultures, enzymology of biomass energy process, bio-ethanol and bio-hydrogen

**W. TENHAEFF**  
PhD MIT, 2009  
electrochemical energy storage, solid state lithium batteries and solid electrolytes, polymer thin films, interfaces and thin film synthesis and characterization, vacuum deposition techniques

**M. Z. YATES**  
PhD 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  
205 Gavett Hall  
Rochester, NY 14627  
(585) 275-4913

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

**Chemical Engineering Education**
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

<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Degree Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. ANTHAMATTEN</td>
<td>Ph.D., MIT, 2001</td>
</tr>
<tr>
<td>S. H. CHEN</td>
<td>Ph.D., Minnesota, 1981</td>
</tr>
<tr>
<td>E. H. CHIMOWITZ</td>
<td>Ph.D., Connecticut, 1982</td>
</tr>
<tr>
<td>D. FOSTER</td>
<td>Ph.D., Rochester, 1999</td>
</tr>
<tr>
<td>T. D. KRAUSS</td>
<td>Ph.D., Cornell, 1998</td>
</tr>
</tbody>
</table>

#### Fuel Cells and Batteries

<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Degree Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. ANTHAMATTEN</td>
<td>Ph.D., MIT, 2001</td>
</tr>
<tr>
<td>J. JORNE</td>
<td>Ph.D., California (Berkeley), 1972</td>
</tr>
<tr>
<td>W. TENHAFF</td>
<td>Ph.D., MIT, 2009</td>
</tr>
<tr>
<td>M. Z. YATES</td>
<td>Ph.D., Texas, 1999</td>
</tr>
</tbody>
</table>

#### Biofuels

<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Degree Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. H. DAVID WU</td>
<td>Ph.D., MIT, 1987</td>
</tr>
<tr>
<td>S. H. CHEN</td>
<td>Ph.D., Minnesota, 1981</td>
</tr>
</tbody>
</table>

#### Solar Cells

<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Degree Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. H. CHEN</td>
<td>Ph.D., Minnesota, 1981</td>
</tr>
<tr>
<td>T. D. KRAUSS</td>
<td>Ph.D., Cornell, 1998</td>
</tr>
<tr>
<td>C. W. TANG</td>
<td>Ph.D., Cornell, 1975</td>
</tr>
</tbody>
</table>

#### Nuclear Energy

<table>
<thead>
<tr>
<th>Faculty Name</th>
<th>Degree Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-U. SCHRÖDER</td>
<td>Ph.D., Darmstadt, 1971</td>
</tr>
</tbody>
</table>

---

Alternative Energy
University of Rochester
206 Gavett Hall
Rochester, NY 14627
(585) 275-4913

Email: chegradinfo@che.rochester.edu
http://www.che.rochester.edu/alternativenergy.htm
The Chemical Engineering Department at Rowan University offers a multidisciplinary research and teaching environment designed to support students in achieving their full potential. State-of-the-art laboratories and classrooms, and an emphasis on fundamental research, industrially-relevant research, and project management are all hallmarks of Rowan Chemical Engineering. The Department has access to Rowan’s two medical schools, two county colleges, and the South Jersey Technology Park. In addition, Rowan has achieved New Jersey state research university designation. Rowan Chemical Engineering offers students an excellent education with numerous opportunities in emerging technologies.

Located in southern New Jersey, Rowan University is nestled between rural and major metropolitan areas. Philadelphia, Baltimore, Washington, D.C., New York City, beaches, bays, mountains, orchards, and farms are all only a short drive away. Rowan University is situated in an optimal location for professional development as well as cultural and recreational enrichments.

Faculty

Cheryl Bodnar · University of Calgary
Kevin D. Dahm · Massachusetts Institute of Technology
Stephanie Farrell · New Jersey Institute of Technology
Zenaida Otero Gephardt · University of Delaware
Robert P. Hesketh · University of Delaware
Mariano J. Savelski, Dept. Head · University of Oklahoma
C. Stewart Slater · Rutgers University
Mary M. Staehle · University of Delaware
Joseph F. Stanzione, III · University of Delaware
Jennifer Vernengo · Drexel University

Research Areas

Membrane Separations · Pharmaceutical and Food Processing Technology · Biochemical Engineering · Systems Biology · Biomaterials · Green Engineering · Controlled Release · Bio-Based Polymers and Composites · 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 · Social Life Cycle Analysis · Experimental Design and Data Analysis · Undergraduate Engineering Education

For additional information

Dr. Joseph F. Stanzione, III · Department of Chemical Engineering
Rowan University · 201 Mullica Hill Road · Glassboro, NJ 08028
Phone: (856) 256-5310 · Fax: (856) 256-5242
E-mail: stanzione@rowan.edu · Web: http://www.rowan.edu/engineering/
Chemical Engineering
at Ryerson University

Ryerson University offers an excellent graduate education in the heart of the vibrant city of Toronto, Ontario, Canada. Ryerson offers more than 100 undergraduate and graduate programs.

The Department of Chemical Engineering offers a versatile and unique program leading to a doctor of philosophy (PhD) degree, a master of applied science (MASc) degree or a master of engineering (MEng) degree. The course-based MEng degree can be completed through either full- or part-time study, while the research-intensive thesis-based MASc and PhD degrees are offered through full-time study.

KEY RESEARCH AREAS

Water/Wastewater and Food Treatment Technologies
- Use of rotating biological contactors and three-phase fluidized beds in treatment of industrial and municipal effluents
- Photo-oxidation and ozone technology applied to treatment of water and wastewaters
- Advanced chemical oxidation and biological processes
- Fluid rheology in food processing
- Fundamental studies of adsorption and absorption of pollutants on solids and liquids
- Bio-adsorption of heavy metals and other contaminants
- Membrane process application in wastewater treatment, membrane fouling
- Biobased ethanol: all processing steps to convert lignocellulose into green ethanol
- Recombinant cellulases in transgenic plants
- Anaerobic digestion of agricultural and wastewaters
- Catalytic ozonation of wastewaters

Polymer and Process Engineering
- Polymer rheology and application to processing techniques
- Kinetics of polymerization
- Nonlinear optical polymers
- Kinetics of phase transition and phase separation in polymer solutions
- Computer simulation of phase separation in polymer systems
- Computer simulation of complex fluids/condensed soft matter
- Process control and optimization: chemical reactors and intra-red/convective dryers
- Liquid crystalline and rod polymers
- Chemical reactive engineering: supercritical fluids, phase equilibria
- Biopolymers and biomaterials
- Interfacial rheology and surface chemistry
- Emulsion stabilization with colloidal particles
- Process modeling and simulation: Artificial Neural Networks (ANN) design
- Micromodels and nanostructured synthesis of advanced materials
- Mixing of fluids with complex rheology
- Flow visualization (phonography and ultrasonic velocimetry)
- Computational fluid mixing
- Non-Newtonian fluid dynamics
- Microporous and mesoporous materials: growth, syntheses, characterizations and surface chemistry
- Kinetic control of chemical processes
- Mass transfer in polymer-solvent systems
- Oil/gas processing and production, SAGD, VAPIX, Hybrid and SA-SAG processes
- Utilization of noble product: fly ash characterizations and uses; biodiesel and energy from agricultural waste and industrial/forest by-products

FACULTY

Manuel Alvarez-Caencà (PhD, Western)
Philipe Chan (PhD, McGill)
Chil-Hung Cheng (PhD, Texas A&M)
Yaser Dahman (PhD, Western)
Ramadan Dhib (PhD, Sherbrooke)
Hieu Doan (PhD, Toronto)
Tom Duheer (PhD, Waterloo)
Dae Kun Hwang (PhD, McGill)
Ali Lohi (PhD, Waterloo)
Mehrieh Mehrvar (PhD, Waterloo)
Farhod Einz-Mofu (PhD, British Columbia)
Ginette Turcotte (PhD, Western)
Simant Upreti (PhD, Calgary)
Stephen Waldman (PhD, Dalhousie)
Jiangning Wu (PhD, Windsor)

FOR MORE INFORMATION

CHEMICAL ENGINEERING GRADUATE PROGRAM
Ryerson University
Phone: 416-979-5000, ext. 7733
Email: chemgrad@ryerson.ca

TO APPLY

YEATES SCHOOL OF GRADUATE STUDIES
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Email: gradadmit@ryerson.ca
www.ryerson.ca/graduate/chemical
As a Department that is recognized in the world, 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!

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- Active research collaboration with the industry, national research centers and institutes
- Top-notch facilities for cutting-edge research under the supervision of world’s renowned researchers
- Strong international research collaboration with universities in America, Europe and Asia
- Over 150 research scholars (80% pursuing Ph.D.) from America, Europe, Middle East and Asia
- Financial assistance, scholarships, tuition fee waivers and awards available for application

Strategic Research & Educational Thrusts
- Biomolecular and Biomedical Engineering
- Chemical Engineering Sciences
- Chemical & BioSystems Engineering
- Environmentally Benign Processing & Sustainability
- Nanostructured and Functionalized Materials & Devices

Our Graduate Programs
Research-based
- Ph.D. and M.Eng.
Coursework-based
- M.Sc. (Chemical Engineering)
- M.Sc. (Safety, Health & Environmental Technology)

International Rankings
Quacquarelli Symonds (QS) World University Rankings 2014/15
- Ranked 1st in QS University Rankings: Asia
- Ranked 5th in QS World University Rankings by Subjects

Times Higher Education (THE) World University Rankings
- Ranked 2nd in THE Asia University Rankings 2015
- Ranked 13th in THE Engineering Rankings 2015

Engineer Your Own Evolution! Reach us at:
National University of Singapore
Department of Chemical & Biomolecular Engineering
4 Engineering Drive 4, #02-09 Singapore 117585
Email: chbe_grad_programs@nus.edu.sg • http://www.chbe.nus.edu.sg • Tel: +65 6516-5031
The Department of Chemical Engineering at USC has emerged as one of the top teaching and research programs in the Southeast. Our national rankings include a top 20 in research expenditures, a top 30 by the National Research Council (NRC), and a top 50 by US News & World Report. 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 2 hours away from the Blue Ridge Mountains and the Atlantic Coast.

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. Visit us online at: http://sc.edu/study/colleges_schools/engineering_and_computing/study/areas_of_study/chemical_engineering

Vol. 49, No. 4, Fall 2015
Our department awarded 9 Doctoral Degrees, 30 Master’s and 71 Bachelor degrees in the Academic Year of 2014-2015. The department has 51 PhD students, 56 Master’s students and 270 undergraduate students currently enrolled. The University of South Florida’s Engineering Graduate program ranks #72 among public institutions by U.S. News & World Report, and is ranked 43rd in the nation for research expenditures, among all U.S. universities, public or private, by the National Science Foundation (2013).

USF is one of the nation’s top 73 public research universities and one of 40 public research universities nationwide with very high research activity that is designated as the community engaged by the Carnegie Foundation for the Advancement of Teaching. USF is one of only four Florida public universities classified by the Carnegie Foundation for the Advancement of Teaching in the top tier of research universities (RU/VH), a distinction attained by only 2.3 percent of all universities.

- 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
- Synfuels Production

chbme@usf.edu • http://chbme.eng.usf.edu • 813-974-3997
Department of Chemical and Biological Engineering

- 2010 NRC rankings place UB CBE in 8th and 9th place for publications and awards per faculty, respectively, among 106 reviewed departments
- Outstanding funding from NIH, NYSTEM, NSF, USAF, AHA, DOE
- 7 NSF CAREER Awards
- 3 members of National Academy of Engineering

Bioengineering research
- Andreadis - Adult and induced pluripotent stem cells for cardiovascular tissue engineering, signaling pathways in cell-cell adhesion and wound healing, biomaterials for protein and gene delivery, lentiviral vectors and lentiviral microarrays for high-throughput gene expression analysis and gene discovery
- Neelamegham - Cell biomechanics, systems biology, thrombosis and hemostasis, glycosciences
- Parashurama - Stem cells, liver tissue engineering and regenerative medicine, advanced imaging modalities
- Park - Biotechnology, protein engineering, simulated dynamics, bioinformatics, drug discovery
- Pfister - Metabolic engineering, heterologous natural product biosynthesis, genetic vaccine design

Modeling and computational research
- Dupuis - Chemistry fundamentals for new energy technologies from multi-physics Multi-scale modeling
- Errington - Molecular simulation, statistical thermodynamics, interfacial phenomena
- Furlani - Multidisciplinary modeling: microfluidics, computational fluid dynamics, mass/heat transfer, multiphase systems, MEMS, nanophotonics, biomagnetics
- Hachmann - Computational chemistry and materials science, virtual high-throughput and Big Data, machine learning, electronic structure theory and methods, quantum effects in catalysis and materials
- Kofke - Statistical physics, molecular modeling and simulation, software engineering
- Lockett - Mass/heat transfer, distillation, separations
- Nitsche - Transport phenomena,ermal absorption, biological membrane and pore permeability

Materials research
- Alexandridis - Self-assembly, directed assembly, complex fluids, soft materials, nanomaterials, interfacial phenomena, amphiphilic polymers, biopolymers, product design
- Cheng - Biodegradable functional polymers and nanostructures, new drug delivery systems, synthetic materials for tissue engineering
- Goyal - Clean energy technologies, high temperature superconductivity, nanomaterials for energy and the environment
- Lin - Membrane materials and processes for gas and vapor separation and water purification
- Lund - Heterogeneous catalysis, chemical kinetics, reaction engineering
- Ruckenstein - Catalysis, surface phenomena, colloids and emulsions, biocompatible surfaces and materials
- Swihart - Synthesis and application of nanoparticles, reactor modeling, computational chemistry, particle nucleation and growth
- Tsianou - Molecularly engineered materials, self-assembly, interfacial phenomena, crystal engineering, bio-inspired materials
- Wu - Advanced electrocatalysts and functional materials for electrochemical energy technologies
- Zukoski - Suspension mechanics, protein crystallization and nanoparticle self-assembly
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
化学工程在田纳西技术大学

佩德罗·阿塞教授兼主席
博士，普渡大学，1990年
电泳，纳米复合材料软材料，环境蛋白质组学，临床诊断学，药物递送，高级氧化，工程教育。

劳拉·阿里亚斯·查韦斯助教教授
博士，耶鲁大学，2014年
聚合物膜：制备和表征，饮用水处理，可持续能源生产，静电纺丝纳米纤维。

约瑟夫·比恩巴奇教授
博士，克利夫兰州立大学，1988年
水泥基材料（水化动力学，材料结构），绿色化学基生物燃料，多尺度材料（模型和性质），工程教育。

巴赫曼·戈哈尔教授，田纳西技术大学副校长
博士，俄亥俄州立大学，1980年
流体力学，燃烧，敏捷制造，技术管理。

温·李教授
教授，数学
博士，特拉华大学，1987年
边界层方法，弥散模型在毛细管中，应用数学。

詹妮弗·帕斯卡尔助教教授
博士，田纳西技术大学，2011年
肿瘤递送，电场驱动的运输，生物医学的数学/计算建模。

杰弗里·赖斯助教教授
博士，加州大学，圣巴巴拉，2007年
开发新型治疗性蛋白质，设计体内细胞培养，合成生物材料。

辛西娅·赖斯助教教授
博士，伊利诺伊州立大学，香槟，2000年
燃料电池，电催化，研究方法。

J·罗伯特·桑德斯助教教授
博士，范德比尔特大学，2001年
生物医学成像，核磁共振成像在临床诊断，药物递送和基因治疗，工程教育。

霍莉·斯特雷茨助理教授
博士，得克萨斯州立大学，奥斯汀，2005年
纳米复合材料和建模，高温材料和耐火材料，聚合物加工。

李云教授
博士，罗德岛大学，2007年
分子动态模拟，材料结构和性能，蛋白质动力学和功能。

学生背景为工程（例如，化学，生物医学，环境，机械，工程物理学，以及其它）或相关学科（如应用数学，物理，物理化学）的学生有一个独特的机会，能够在田纳西技术大学的跨学科工程博士项目中追求其学位教育，该学科是化学工程的一个强大伙伴。该项目的学生已经获得了国家科学基金会和国家健康研究所的博士后奖学金和领导研究职位，在国内和国际知名企业。凭借高程度的博士水平工作，获奖的杰出教授与来自工程学院，商学院和艺术与科学学院的同事们进行合作，一起开发的具有破坏性的研究成果在

具有破坏性的研究成果在

先进的材料（纳米复合材料，聚合物膜等），

电子化系统（电催化，电泳，燃料电池，等），

生物化系统（分子基生物医学，临床诊断学，微生物分离）。

此外，对增进其在工程教育领域的专业知识感兴趣的学生将有发展方法支持国家工程院2020年愿景的令人兴奋的途径。

该领域和学生定期在包括AIChE，ACS，ACerS，ASEE，AES和其他支持的年度会议中展示他们的研究，学生经常因他们的杰出贡献而获奖。

田纳西技术大学化学工程部

35013 • 库克维尔，TN 38505-0001 • che@tntech.edu • 电话(931) 372-3297
Fax (931) 372-6352 • http://www.tntech.edu/che

田纳西技术大学是一个在田纳西州的联邦立法机关建立的大学。田纳西技术大学不歧视基于种族，肤色，宗教，国籍，性，性取向，性别认同/表达，残疾，年龄，退伍军人身份，遗传信息或任何其他法律保护等级。有关歧视政策的查询，请联系equity@tntech.edu.

田纳西技术大学的非歧视政策可在www.tntech.edu/aa中找到。
What Starts Here Changes The World

QUALITY FACULTY
Our award-winning faculty are dedicated to cultivating a strong mentoring environment, offering an unsurpassed experience for graduate students. Our professors and lecturers have earned recognition by the American Institute of Chemical Engineers and membership to the National Academies, and several are among the top 25 most cited chemical engineers in areas such as nanotechnology and energy.

FACILITIES
Chemical engineering is one of seven departments within the Cockrell School of Engineering, which provides many cross-disciplinary research projects and programs. Research opportunities for chemical engineering students are available in more than 20 centers, including the Engineering Education and Research Center which will open in 2017. The EERC will be a hub of collaboration that connects leaders across industries and institutions.

SUBSTANTIAL FUNDING
We offer generous financial packages for both domestic and international students that include fellowships, paid teaching or research positions, health insurance and tuition coverage.

RESEARCH AREAS
Approximately $23 million in annual research funding supports programs in: advanced materials, polymers and nanotechnology; biotechnology; energy; environmental engineering; modeling and simulation; and process engineering.

ENTREPRENEURIAL CULTURE
In the past 10 years, roughly a third of our faculty have started or helped spin off successful companies as a result of research done at UT Austin, with technologies such as antibody therapies for cancer and glucose monitoring. More than 100 of our alumni are now teaching and conducting research as faculty of some of the greatest universities around the world.

DYNAMIC LOCATION
Austin, Texas, the state’s vibrant capital city, offers more than just SXSW and BBQ. Consistently ranked in the top of best-city lists, Austin has become a major tech industry hub, with an ever-increasing number of booming startups and large companies calling the city home. Austin continues to be one of the fastest-growing, most innovative cities in the country. The city also boasts a sunny, temperate climate year-round and is chock-full of history, culture, live music and outdoor recreation.

Program Rankings & Facts

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<th>US News &amp; World Report, 2014</th>
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<td>#2</td>
<td>National Research Council Regression Based, 2010</td>
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<tr>
<td>#5</td>
<td>National Research Council Survey Based, 2010</td>
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Students
- 186 graduate students
- 37% international students
- 29 Ph.D. degrees conferred in 2014

Contact
Graduate Coordinator
Phone: (512) 471-6991
Email: chemegrad@utexas.edu

Faculty
- 30 Ph.D. supervising faculty
- 250 faculty publications each year
- 84 patents issued in the last five years

#1 in job growth
#3 coolest city
#5 in livability for people 35 and under

Austin, TX
RESEARCH AREAS:
Biomedicine and Biomolecules
Biosciences
Biotechnology
Catalysis
Complex Fluids
Computational Chemical Engineering
Energy
Environment
Materials
Microelectronics
Microfluidics
Multiscale Systems Engineering
Nanotechnology
Process Safety
Process Systems Engineering
Reaction Engineering
Sustainability
Thermodynamics

GRADUATE PROGRAM:
115 students (Fall 2014)
Top 10 in research funding
Financial aid for all doctoral students
up to $30,000/yr plus tuition, fees and
medical insurance benefits
Institutional ranking (U.S. News & World Report)
16th - Public
26th - Overall

FOR MORE INFORMATION:
Graduate Admissions Office
Artie McFerrin Department of Chemical Engineering
Dwight Look College of Engineering
Texas A&M University, College Station, TX 77843-3122
(979) 845-3361 | engineering.tamu.edu/chemical
TEXAS TECH UNIVERSITY
Department of Chemical Engineering

Research Areas

Bioengineering
Energy and Sustainability
Polymers and Materials
Simulation and Modeling in Chemical Engineering

www.depts.ttu.edu/che

Contact Information
Dr. Siva Vanapalli
Associate Professor and
Graduate Advisor
siva.vanapalli@ttu.edu

Chau-Chyun Chen
Massachusetts Institute of Technology
Molecular thermodynamics, phase equilibria, process modeling and simulation

Harvinder Singh Gill
Georgia Institute of Technology
Drug and vaccine delivery, bionanomaterials, immunomodulation

Ronald C. Hedden
Cornell University
Networks, gels, and elastomers, biofuels, polymer processing

Sheima Jatib-Khatib
University of Madrid
Heterogeneous catalysis, Operando Spectroscopy, membrane reactors

Rajesh Khare
University of Delaware
Molecular dynamics and simulations of polymers and soft matter

Carla Lacerda
Colorado State University
Mitrval heart valve degeneration: models, mechanisms, and prevention

Wei Li
University of Toronto
Cell/polymer interactions, cell microenvironments, biomedical devices

Jeremy Marston
University of Birmingham
Experimental fluid dynamics, granular media, high-speed imaging

Gregory B. McKenna
University of Utah
Polymer and soft matter physics, rheology, nanorheology, nanomechanics

Nurxat Nuraje
City University of New York
Enhanced oil recovery, photocatalysis, renewable energy

Al Sacco, Jr. (Dean)
Massachusetts Institute of Technology
Transition metal and acid catalysts, zeolite synthesis

Sindee L. Simon (Chair)
Princeton University
Physics of glasses, nanoconfined reactions, calorimetry, dilatometry

Siva A. Vanapalli (Graduate Advisor)
University of Michigan
Microfluidics, mechanics of cells and biopolymers, colloidal assembly

Mark W. Vaughn (Undergrad. Advisor)
Texas A & M University
Nitric oxide in microcirculation, membrane transport

Brandon L. Weeks (Associate Chair)
Cambridge University
High explosives, nanolithography, microcantilever, crystal growth

Theodore F. Wiesner
Georgia Institute of Technology
Solar energy, hydrogen production, CO₂ mitigation
The Department of Chemical & Environmental Engineering at The University of Toledo offers graduate programs leading to M.S. and Ph.D. degrees. We are located in state of the art facilities in Nitschke Hall and our dynamic faculty offer a variety of research opportunities in contemporary areas of chemical engineering.

SEND INQUIRIES TO:
Graduate Studies Advisor
Chemical & Environmental Engineering
The University of Toledo
College of Engineering
2801 W. Bancroft Street
Toledo, Ohio 43606-3390

419.530.8080 • www.che.utoledo.edu
cheedept@eng.utoledo.edu
The University of Toronto is the highest ranked Chemical Engineering program in Canada. (2015 QS World Ranking)

From the environment and human health to climate change and sustainable energy, the world is facing tremendous challenges. We have one of the strongest research and teaching faculties in North America with an outstanding international reputation for innovative research addressing urgent issues in sustainable energy/materials, water, health, finance, resource extraction and bioprocessing.

Our unique blend of engineering and applied chemical & biochemical sciences will give you a powerful combination of skills. You will do high-impact work on real-world problems in our exceptional facilities, in the heart of one of the most vibrant and multi-cultural cities in the world. We are part of Canada’s largest university and offer superb infrastructure, strong industrial connections, many opportunities for professional development, international exchanges, a collegial atmosphere, and guaranteed student funding for MASc and PhD students.

33 faculty members (2014)  $15M total research funding (2014)
245 graduate students (2014)  20 spin-off companies since 1970

RESEARCH AREAS:
Biomolecular & biomedical engineering
Bioprocess engineering
Chemical & material process engineering
Environmental science & engineering
Informatics
Pulp & paper
Surface & interface engineering
Sustainable energy

Graduate Research Days 2016
In February 2016 we will host select applicants for an expenses-paid trip to U of T to learn more about our graduate research programs. Meet our professors, tour labs and interact with current students at this exclusive event. Visit our website to find out more.

APPLY NOW
www.chem-eng.utoronto.ca/graduate

For more information:
Graduate Coordinator, Dept. of Chemical Engineering & Applied Chemistry
University of Toronto, 200 College St., Room 212, Toronto, ON, MSS 3E5
416.946.3987 I gradassist.chemeng@utoronto.ca

Chemical Engineering & Applied Chemistry
UNIVERSITY OF TORONTO
Research Areas:

- Batch Process Modeling, Optimization, Systems Engineering
- Biomaterials, Tissue Engineering
- Biomolecular Engineering, Cell Engineering
- Bionanotechnology, Biosensors, Smart Biopolymers
- 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
Kyongbum Lee, Department Chair Ph.D., M.I.T.
Ayse Asatekin Ph.D., M.I.T.
Maria Flytzani-Stephanopoulos Ph.D., University of Minnesota
Christos Georgakis Ph.D., University of Minnesota
Jerry H. Meidon Ph.D., M.I.T.
Derek Mess Ph.D., M.I.T.
Nikhil U. Nair Ph.D., University of Illinois
Matthew Panzer Ph.D., University of Minnesota
Daniel R. Ryder Ph.D., Worcester Polytechnic Institute
Nak-Ho Sung, Emeritus Ph.D., M.I.T.
Emmanuel S. Tzanakakis Ph.D., University of Minnesota
James Van Deventer Ph.D., California Institute of Technology
Ken Van Wormer, Emeritus Ph.D., M.I.T.
Hyunmin Yi Ph.D., University of Maryland

Adjunct Faculty
Linda Abriola Ph.D., Princeton University
Soha Hassoun Ph.D., University of Washington
David L. Kaplan Ph.D., Syracuse University
Qiaoqing Xu Ph.D., Harvard University
Darryl Williams Ph.D., University of Maryland

Visit our website!
http://engineering.tufts.edu/chbe

For more information:
Tufts University
Chemical and Biological Engineering
Science & Technology Center
4 Colby Street, Room 148
Medford, MA 02155
Phone: 617-627-3900; Fax: 617-627-3991
E-mail: 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

OUR FACULTY AND RESEARCH
Julie N. L. Albert | Assistant Professor
Nanosctructured Polymeric Materials, Stimuli-responsive Materials, Thin Film Morphologies, Surface Science, Combinatorial Methods, Solar Energy, Cancer Metastasis

Hank Ashbaugh | Associate Professor
Classical Thermodynamics and statistical Mechanics, Molecular Simulation, Multi-Scale Modeling of Self-Assembly and Nanostructured Materials

W T. Godboy | Associate Professor
Gene Delivery, Cellular Engineering, Molecular Aspects of Nonviral Transfection, Biomaterials

Vijay John | Professor
Self-assembly and Nanostructured materials, Polymer/Nanocomposites, Biomolecular Materials, Microemulsions

Brian S. Mitchell | Professor
Nanostructured Materials, Fiber Technology, Materials Processing, Composites

Kim C. O’Connor | Professor
Stem Cell Technology: mesenchymal cells, clonal heterogeneity, cell signaling, aging, regenerative therapies

W T. Godboy | Associate Professor

Noshir S. Pesika | Assistant Professor
Nanomaterial Synthesis and Characterization, Surface functionalization and Rheology, Bio-inspired Materials, Surface Science, Electrochemistry

Lawrence R. Pratt | Professor
Statistical Mechanics and Thermodynamics, Theory of Liquids and Solutions, Molecular Biology, Electrochemical Capacitors and Energy

Anne Skaja Robinson | Professor and Department Chair
Molecular and cellular engineering for improved protein production, developing cellular biosensors for understanding and control of disease

Katie C. Russell | Professor of Practice
Stem cell technology, clonal heterogeneity, flow cytometry, sorting strategies for mesenchymal stem cell enrichment

Daniel F. Shantz | Professor
New materials to address challenges in energy and sustainability

THE TULANE CBE GRADUATE EXPERIENCE
- Tulane’s CBE program is one of the oldest Chemical Engineering programs in the United States
- The small faculty (11) and graduate student body (35) leads to a student-first focus
- Multiple interdisciplinary research initiatives across academic programs
- CBE is actively engaged in university initiatives in Health, Energy, and Environment
- Tulane is located in New Orleans, a vibrant and culturally rich city

An environment that fosters an intellectually challenging, personal, and rewarding graduate experience

For Additional Information, Please Contact
Dr. Daniel F. Shantz, Graduate coordinator
Tel. (504) 862-3170 E-mail, dshantz@tulane.edu
Visit us at http://tulane.edu/sse/cbe
Engineering the World

The University of Tulsa

The University of Tulsa is Oklahoma’s oldest and largest independent university. Approximately 4,200 students pursue more than 70 major fields of study and graduate programs in more than 25 disciplines.

Tulsa, Oklahoma

Off-campus activities abound in Tulsa, one of the nation’s most livable cities. Our temperate climate, with four distinct seasons, is perfect for year-round outdoor activities. With a metropolitan population of 888,000, the city of Tulsa affords opportunities for students to gain internship and work experience in its dynamic data processing, petroleum, medical, and financial industries. One can also enjoy world-class ballet, symphony and theatre performances, and exhibits in the cultural community. Annual events include Mayfest, Oktoberfest, the Chili Cook-off and Bluegrass Festival, the Tulsa Run, and the Jazz and Blues festivals.

Chemical Engineering at TU

TU enjoys a solid international reputation for expertise in the energy industry, and offers materials, environmental and biochemical programs. The department places particular emphasis on experimental research, and is proud of its strong contact with industry.

The department offers a traditional Ph.D. program and three master’s programs:
• Master of Science degree (thesis program)
• Master of Engineering degree (a professional degree that can be completed in 18 months without a thesis)
• Special Master’s degree for nonchemical engineering undergraduates

Financial aid is available, including fellowships and research assistantships.

The Faculty

S.A. Cremaschi • Engineering complex systems, optimization under uncertainty
D.W. Crunkleton • Alternative energy, transport phenomena
L.P. Ford • Kinetics of dry etching of metals, surface science
T. W. Johannes • Directed evolution, biocatalysis, biosynthesis, metabolic engineering
F.S. Manning • Industrial pollution control, surface processing of petroleum
C.L. Patton • Thermodynamics, applied mathematics
G.L. Price • Zeolites, heterogeneous catalysis
K.L. Sublette • Bioremediation, biological waste treatment, ecological risk assessment
K.D. Wisecarver • Multiphase reactors, multiphase flows

Further Information
Graduate Program Director • Chemical Engineering Department
The University of Tulsa • 800 South Tucker Drive • Tulsa, Oklahoma 74104-3189
Phone (918) 631-2227 • Fax (918) 631-3268
E-mail: chegradadvisor@utulsa.edu • Graduate School application: 1-800-882-4723

The University of Tulsa has an Equal Opportunity/Affirmative Action Program for students and employees.
The University of Utah's Department of Chemical Engineering provides cutting-edge graduate research opportunities in energy and fuels, biotechnology, environmental engineering, nanotechnology, medicine, and pharmacy. Our faculty is tightly integrated with the Institute for Clean and Secure Energy, Nano Institute of Utah, the Energy and Geosciences Institute, and the Nuclear Engineering Program. Students have access to state-of-the-art laboratory facilities and a network of faculty with diverse research expertise.

In addition to high-quality research, you will find our faculty is dedicated to teaching. Many professors have earned outstanding teaching awards and routinely rank among the top instructors in the College of Engineering. Graduate students enjoy the collegiality of our department and location of our campus, which provides many recreational opportunities outside the classroom and laboratory.

Our department offers the following degrees:
- PhD in Chemical Engineering*
- MS in Chemical Engineering*
- MS in Petroleum Engineering (distance or on-campus)
- MS/MBA in collaboration with the David Eccles School of Business

*Student financial support for these degrees is available through fellowships and research assistantships

For more information about our graduate programs please visit our website at che.utah.edu/graduate

STUDENT SUCCESS:
Our former graduate students are now employed at top-tier, nationally recognized corporations, academic institutions, and laboratories such as:

- Intel
- John Zink Company LLC
- National Renewable Energy Laboratory
- Conoco Phillips
- GE Energy
- Afton Chemical
- USG Corporation
- Devon Energy
- CD Adapco
- Halliburton
- BP
- USG Corporation
- Brigham Young University

RECREATION:
Utah is home to five national parks and is legendary for outdoor recreation activities. The Wasatch mountains offer excellent hiking and mountain biking and include 10 world-class ski resorts within 30 minutes of Salt Lake City.

FACULTY:

Anthony Butterfield  
Dolly Chitta  
Milind Deo (Chair)  
Eric Eddings  
Andrew Fry  
Michael Hoepfner  
Tatjana Jevremovic  
JoAnn Lighty  
Jules Magda  
John McLennan  
Manoranjan Misra  
Swomitra Mohanty  
Agnes Ostafin  
Marc Porter  
Terry Ring  
Richard Roehner  
Geo_rey Silcox  
Stuart Simmons  
Mikhail Skliar  
Philip Smith  
Sean Smith  
Jennifer Spiriti  
James Sutherland  
Jeremy Thormock  
Edward Trujillo  
Jost Wendt  
Kevin Whitty
Graduate Study Leading to the Ph.D. and M.S. Degrees

Graduate work in chemical engineering provides an opportunity for study and research at the cutting edge - to contribute to shaping a new model of what chemical engineering is and what chemical engineers do. At Vanderbilt University we offer a broad range of research projects in chemical and biomolecular engineering, with wide ranging opportunities for interdisciplinary work and professional development. Focus areas include:

- Adsorption and nanoporous materials
- Alternative energy and biofuels
- Biomaterials and tissue engineering
- Computational molecular engineering and nanoscience
- Metabolic engineering
- Microelectronic and ultra-high temperature materials
- Nanoparticles for drug and gene delivery
- Surface modification and molecular self-assembly

Research assistantships offer a competitive stipend, full tuition waiver, and health insurance. Additionally School and University fellowship awards are available to outstanding applicants. To find out more visit:

http://engineering.vanderbilt.edu/chbe/

Vanderbilt, ranked in the top 20 nationally for its leadership in both research and teaching, is located on 330 park-like acres just one and one-half miles from downtown Nashville, one of the most vibrant and cosmopolitan mid-sized cities in the United States. Ten schools offer both an outstanding undergraduate and a full range of graduate and professional programs. With a prestigious faculty of more than 2,800 full-time and 300 part-time members, Vanderbilt attracts a diverse student body of approximately 6,500 undergraduates and 5,300 graduate and professional students from all 50 states and over 90 foreign countries.

For more information:
Director of Graduate Studies
Department of Chemical & Biomolecular Engineering
Vanderbilt University • VU Station B 351604
Nashville, TN 37235-1604
Email: chegrad@vanderbilt.edu
Graduate Studies in Chemical Engineering

...fulfilling Thomas Jefferson’s vision

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.

Graduate Admissions
Dept. of Chemical Engineering
102 Engineers' Way
P.O. Box 400741
University of Virginia
Charlottesville, VA 22904-4741
434.924.7778

E-mail: cheadmis@virginia.edu
Website: www.che.virginia.edu

Giorgio Carta, PhD, University of Delaware
Bioseparations, protein chromatography, transport phenomena in adsorption and ion exchange

Joshua J. Choi, PhD, Cornell University
Nanomaterials for solar energy conversion, nanoparticle self-assembly, materials chemistry, optoelectronic devices

Robert J. Davis, PhD, Stanford University
Heterogeneous catalysis, reaction kinetics, conversion of renewable resources

Roseanne M. Ford, PhD, University of Pennsylvania
Mass transfer and chemical reaction in biological and environmental systems

Geoffrey M. Geise, PhD, The University of Texas at Austin
Macromolecular engineering for separations and clean energy, water purification, membrane design, ion and water transport, polymer science

Gaurav Giri, PhD, Stanford University
Pharmaceutical crystallization, microreactors, microfluidics, and metal-organic frameworks (MOFs)

David L. Green, PhD, University of Maryland, College Park
Nanoparticle engineering, complex fluids, colloid and interface science, soft materials

Gary M. Koenig, Jr., PhD, University of Wisconsin-Madison
Materials for energy storage, electrochemistry, colloid and interface science, nanomaterials, soft materials

Kyle Lampe, PhD, University of Colorado
Neural tissue engineering, biomaterials, drug delivery, redox regulation of stem cell fate, engineering cell-interactive microenvironments

Chemical Engineering Education
Chemical Engineering at Virginia Tech

**Faculty . . .**

Modeling of chemical and biological systems

**Donald G. Baird** (Wisconsin)
Polymer processing, non-Newtonian fluid mechanics

**Michael J. Bortner** (Virginia Tech)
Polymer nanocomposites, interfaces, morphology and structure-property relationships

**David F. Cox** (Florida)
Catalysis, ultrahigh vacuum surface science

**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

**Ayman M. Karim** (New Mexico)
Heterogeneous catalysis, nucleation/growth of colloidal nanoparticles, microreactors for in-situ/operando characterization

**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

**Stephen M. Martin** (Minnesota)
Soft materials, self-assembly, interfaces

**Padma Rajagopalan** (Brown)
Polymeric biomaterials, cell and tissue engineering

**Rong Tong** (Illinois)
Polymer chemistry, biomaterials, nanomedicine

**Abby R. Whittington** (Illinois)
Tissue engineering, controlled release of proteins

**Hongliang Xin** (Michigan)
Computational catalysis, kinetic theory of electron transfer processes, understanding-driven catalyst screening

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245 Goodwin Hall, 635 Prices Fork Road, Virginia Tech, Blacksburg VA 24061
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Technical University of Berlin
Heterogeneous catalysis: from fundamentals to industrial applications

Su Ha
University of Illinois, Urbana-Champaign
Energy generation from alternative fuels
Jean-Sabin McEwen
Dalhousie University, Canada
Atomic modeling of catalytic processes for energy and environmental applications
Steven Saunders
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Nanotechnology for novel catalytic systems, sustainable solvent technologies

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Microbial adhesion, friction and sensing
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Hacettepe University
Biomimetic engineering

Haluk Resat
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Systems biology of cell signaling, receptor signaling networks, metabolic networks, terrestrial ecology and microbial communities

ENGGINEERING EDUCATION
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University of Oregon
Engineering and entrepreneurship pedagogy, technology development and clinical applications of biomedical instrumentation
David Thiessen
University of British Columbia
Biomass chemistry, biomass conversion to bioproducts and bioenergy

ADDITIONAL RESEARCH
James Petersen
Director
Iowa State University
Bioremediation of contaminated aquatic systems, modeling of biological processing operations and online optimization of biological processes

Birgitte Ahlring
Battelle Distinguished Professor
University of Copenhagen
Microbiology and bioterrorism

David Lin
Northwestern University
Integrated mechanical properties of skeletal muscle and spinal reflexes

Anita Vasavada
Northwestern University
Biomechanics and neural control of the musculoskeletal system, focusing on the human head and neck system

Xiao Zhang
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James A. Dumesic
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Michael D. Graham
Fluid mechanics; complex fluids; microfluidics; applied and computational mathematics

George W. Huber
Heterogeneous catalysis; renewable fuels and chemicals; biomass and natural gas conversion

Daniel J. Klingenberg
Colloid science; complex fluids; suspension rheology

Thomas F. Kuech
Advanced materials processing; solid-state, electronic, and nanostructured materials; interface science; alternative energy materials

David M. Lynn
Soft materials; nanotechnology; polymers; biotechnology; drug delivery

Christos T. Maravelias
Production planning and scheduling; supply chain management; process synthesis; novel material discovery

Manos Mavrikakis (Chair)
Thermodynamics; kinetics and catalysis; surface science; computational chemistry; fuel cells; sensors; nanoscience

Regina M. Murphy
Biomedical engineering; protein-protein interactions; neurodegenerative disorders

Sean P. Palecek
Stem cell engineering; antimicrobial agents; cell signaling

Brian F. Pfleger
Synthetic biology; biotechnology; protein engineering; sustainable chemical production

James B. Rawlings
Process modeling, dynamics and control; nonlinear model predictive control; chemical reaction engineering

Jennifer L. Reed
Systems biology; computational biology; metabolic engineering; microbial interactions

Thatcher W. Root
Green chemistry; renewable resources; catalysis; spectroscopy

Eric V. Shustka
Drug delivery; protein engineering; biopharmaceutical design

Ross E. Swaney
Process design, synthesis, modeling and optimization

Reid C. Van Lehn
Nano-bio interactions; soft materials; cell membranes; engineered nanomaterials; molecular simulation

John Yin
Systems biology; virus-cell interactions; immunology; microfluidics

Victor M. Zavala
Large-scale optimization; dynamics and control; energy systems

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Terri A. Carnesano, PhD., Pennsylvania State University

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William M. Clark, PhD., Rice University

Catalysis & Reaction Engineering • Fuel Cells & Hydrogen
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Anthony G. Dixon, PhD., University of Edinburgh

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Nikolaos K. Kazantzis, PhD., University of Michigan

Chemical Process Safety • Air Pollution Control • Pollution Prevention
Stephen J. Kmieciak, PhD., WPI

Inorganic Membranes • Hydrogen Separation & Membrane Reactors
Yi Hua Ma, ScD., MIT

Biomaterials • Polymer Films & Interfaces
Amy M. Peterson, PhD., Drexel University

Kinetics & Reactor Analysis • Particulate Synthesis • Water Purification
Robert W. Thompson, PhD., Iowa State University

Renewable Energy • Liquid & Biomass Fuels • Reaction Engineering
Michael T. Timko, PhD., MIT

Bionanotechnology • Bioseparations • BioMEMS Microfluidics
H. Susan Zhou, PhD., University of California, Irvine

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- Membranes
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- Regenerative Medicine

**Faculty**
- Hertanto Adidharma, Louisiana State University
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- Saman Aryana, Stanford University
- David Bagley, Cornell University
- David Bell, Colorado State University
- Maohong Fan, Osaka University; Iowa State University
- Lamia Goual, Imperial College London
- Joseph Holies, University of Virginia
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- Luis Felipe Pereira, Stony Brook University
- Mohammad Piri, Imperial College London
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• Eric Dufresne (Mechanical Engineering & Materials Science)
• Tarek Fahmy (Biomedical Engineering)
• Thomas Graedel (School of Forestry & Environmental Studies)
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**M.S. and Ph.D. Degree Programs**

**Faculty and Research Interests**

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<th>Name</th>
<th>Institution</th>
<th>Research Areas</th>
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<td>Morris D. Argyle</td>
<td>Berkeley</td>
<td>heterogeneous catalysis</td>
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<tr>
<td>Larry L. Baxter</td>
<td>(BYU)</td>
<td>combustion of fossil and renewable fuels</td>
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<tr>
<td>Bradley C. Bundy</td>
<td>(Stanford)</td>
<td>protein production and engineering</td>
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<td>Alonzo D. Cook</td>
<td>(MIT)</td>
<td>tissue and biomedical engineering</td>
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<tr>
<td>Thomas H. Fletcher</td>
<td>(BYU)</td>
<td>pyrolysis and combustion</td>
</tr>
<tr>
<td>John H. Harb</td>
<td>(Illinois)</td>
<td>coal combustion, electrochemical engineering</td>
</tr>
<tr>
<td>William C. Hecker</td>
<td>(UC Berkeley)</td>
<td>kinetics and catalysis</td>
</tr>
<tr>
<td>John Hedengren</td>
<td>(UT Austin)</td>
<td>modeling and optimization for energy systems</td>
</tr>
<tr>
<td>Thomas A. Knotts</td>
<td>(University of Wisconsin)</td>
<td>molecular modeling</td>
</tr>
<tr>
<td>Randy S. Lewis</td>
<td>(MIT)</td>
<td>biochemical and biomedical engineering</td>
</tr>
<tr>
<td>David O. Lignell</td>
<td>(Utah)</td>
<td>computational reacting flow</td>
</tr>
<tr>
<td>Matthew J. Memmott</td>
<td>(MIT)</td>
<td>nuclear power &amp; safety, reactor design</td>
</tr>
<tr>
<td>William G. Pitt</td>
<td>(Wisconsin)</td>
<td>materials science</td>
</tr>
<tr>
<td>Dean R. Wheeler</td>
<td>(Berkeley)</td>
<td>molecular electrochemistry</td>
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<tr>
<td>W. Vincent Wilding</td>
<td>(Rice)</td>
<td>thermodynamics, environmental engineering</td>
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**J. Csernica, Chair (Ph.D., M.I.T.)**

Diffusion in polymers, polymer surface modification

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Thin films, surface chemistry

**W.E. King (Ph.D., Pennsylvania)**

Photodynamic therapy, hemodialysis

**J.E. Maneval (Ph.D., U.C. Davis)**

NMR methods, membrane and novel separations

**M.J. Prince (Ph.D., U.C. Berkeley)**

Environmental barriers, instructional design

**T.M. Raymond (Ph.D., Carnegie Mellon)**

Atmospheric science, organic aerosols, air pollution

**R.C. Snyder (Ph.D., U.C. Santa Barbara)**

Conceptual design crystallization

**W.J. Snyder (Ph.D., Penn State)**

Polymer degradation, kinetics, drag reduction

**M.A.S. Vigeant (Ph.D., Virginia)**

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**B.M. Vogel (Ph.D., Iowa State)**

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**K. Wakabayashi (Ph.D., Princeton)**

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Vol. 49, No. 4, Fall 2015
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Faculty and Research Areas:

- **Wudneh Admassu**—Transport Phenomena, Gas Separations, Biochemical Engineering with Environmental Applications
- **Eric Aston**—Surface Science, Thermodynamics, Scanning Probe Microscopy
- **Indrajit Charit**—Energy Materials (Nuclear and Fossil), High Temperature Mechanical Behavior of Materials, Nanostructured Materials, Advanced Processing and Joining Techniques
- **Samrat Choudhury**—Phase-field Simulations of Ferroelectric Materials, ab initio-based Multiscale Modeling of Diffusion in Metallic Iron Alloys, Structure-chemistry Relationships of Complex Interfaces.
- **Dean Edwards**—Application of Computer Modeling and Material Development to Battery Research
- **James Moberly**—Microbial Fuel Cells, Bioenergy, Bioremediation, Metal/Microbe Interactions, Environmental Biotechnology
- **Batric Pesic**—High and Low Temperature Metal Separation Methods
- **Krishnan Raja**—Nanomaterials for Energy Conversion & Storage, Nuclear Materials, Aqueous and Non-aqueous Electrochemistry, and Environmental Degradation of Materials
- **Mark Roll**—Polymers, Composites, Solid Electrolytes and Thin Film Materials
- **Soumya K. Srivastava**—Microfluidics, Bio-separations, Designing Lab-on-a-Chip System for Medical Diagnostic Applications Using Electrokinetics Modeling & Simulations, Educational Research
- **Haiyan Zhao**—Catalysis & Kinetics, Materials Characterization, Renewable Energy & Processing (Idaho Falls)

For more information, contact our department Graduate Advisor Email: che@uidaho.edu, Phone 208-885-7572, http://www.uidaho.edu/engr/cme/

The northern Idaho region offers a year round complement of outdoor activities including hiking, whitewater rafting, skiing and camping!

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**LAMAR UNIVERSITY**

**GRADUATE STUDY IN CHEMICAL ENGINEERING**

- Master of Engineering
- Master of Engineering Science
- Master of Environmental Engineering
- Doctor of Engineering
- Ph.D. of Chemical Engineering

**RESEARCH AREAS**

- Process Simulation, Control and Optimization
- Heterogeneous Catalysis, Reaction Engineering
- Air Quality Modeling, Fluidization Engineering
- Transport Properties, Mass Transfer, Gas-Liquid Reactions
- Computer-Aided Design, Henry’s Law Constant
- Thermodynamic Properties, Water Solubility
- Air Pollution, Bioremediation, Waste Minimization
- Sustainability, Pollution Prevention
- Fuel Cell Applications
- Polymer Nanocomposite Fabrication and Applications
- Material Processing

For further information, contact
Graduate Admissions Coordinator • Department of Chemical Engineering • Lamar University • P.O. Box 10053 • Beaumont, TX 77710
Website: http://dept.lamar.edu/chemicalengineering • Phone: 409-880-8784

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University of Missouri
DEPARTMENT OF CHEMICAL ENGINEERING

Matthew T. Bernard, PhD (Washington-Seattle)
Biomaterials * Tissue Engineering * Surface Science
Paul C. H. Chan, PhD (CalTech)
Reactor Analysis * Fluid Mechanics
Tushar Ghosh, PhD (Oklahoma State)
Adsorption * Heat Transfer * Nuclear Engineering
Karl D. Hammond, PhD (UMass Amherst)
Zeolites * Fusion Energy * Computational Simulation
Patrick J. Pinhero, PhD (Notre Dame)
Nuclear Materials * Nanofabrication * Solar Energy
David G. Retzloff, PhD (Pittsburgh)
Reactor Analysis * Materials
Galen I. Suppes, PhD (Johns Hopkins)
Biofuel Processing * Renewable Energy * Convection Batteries
Bret D. Ulery, PhD (Iowa State)
Immunology * Tissue Engineering * Peptide Amphiphiles
Yangchuan Xing, PhD (Yale)
PEM Fuel Cells * Electro/Photo Catalysis * Li Ion Batteries

The University of Missouri is one of the most comprehensive institutions in the nation and is situated on a beautiful land grant campus halfway between St. Louis and Kansas City, and a little over an hour from the recreational Lake of the Ozarks. The Department of Chemical Engineering offers MS and PhD programs in addition to its undergraduate BS degree. Program areas include: surface science, biodegradation, biomaterials, nanomaterials, nuclear energy, ionic liquids, tissue engineering, chemical kinetics, photocatalysis, computational materials science, and materials science. Faculty expertise encompasses a wide variety of specializations and research within the department is funded by industry, government, non-profit and institutional grants in many research areas.

Go Online: http://che.missouri.edu or Email: retzloffd@missouri.edu or Call: 573.882.4877

UNIVERSITY OF NEVADA, RENO

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chemengr@unr.edu
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(775) 327-5059 [fax]

Chemical Engineering
Univ. of Nevada, Reno
Reno, NV 89557-0388
USA

Research Areas
Biomaterials
Biomedical Simulation
Process Safety
Polymer Engineering
Process Control
Process Simulation
Molecular Simulation
Fluidization
Process Design
Separation Processes
Pollution Prevention
Polymers
Phase Equilibria
Reaction Engineering
Renewable Energy
Nanotechnology

Faculty
• Charles J. Coronella (Univ. of Utah)
• Alan Fuchs, Chair (Tufts University)
• Hongfei Lin (Louisiana State Univ.)
• Vaidyanathan Subramanian (Univ. of Notre Dame)
• Victor R. Vasquez (Univ. of Nevada, Reno)

Enjoying the clear skies and moderate climate of Northern Nevada, UNR is convenient to downtown and only 45 minutes from Lake Tahoe.
Graduate Study in Chemical Engineering
(MS & PhD Degrees)

Research Areas:

- Biochemical Engineering (Rivero)
- Bionanotechnology (Bothun)
- Colloidal Phenomena, Nanotechnology (Bose)
- Corrosion (Brown)
- Molecular Simulations, Polymers (Greenfield)
- Pharmaceutical Engineering (Worthen)
- Pharmaceutical Engineering (Meenach)
- Process Simulation (Lucia)
- Sensors, Thin Film Material Science (Gregory)
- Biomaterials (Kennedy)

For information and applications, see website:
http://egr.uri.edu/che/graduate/
email: chegradinquiry@egr.uri.edu

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ROSE-HULMAN
INSTITUTE OF TECHNOLOGY

DEPARTMENT OF CHEMICAL ENGINEERING

D.D. Anastasio, Ph.D., UCONN
Engineering Pedagogy, Osmotic Processes

H.C.S. Chenette, Ph.D., Clemson
Polymer-functionalized Membranes

M.H. Hariri, Ph.D., Manchester, U.K.
Energy, Environment and Safety

D.B. Henthorn, Ph.D., Purdue
Biomaterials, Diagnostic & Therapeutic Devices

K.H. Henthorn, Ph.D., Purdue
Particle Technology, Microfluidics

S.J. McClellan, Ph.D., Purdue
Colloidal and Interfacial Phenomena, Drug Delivery

G.T. Neumann, Ph.D., Notre Dame
Heterogeneous Catalysis, Materials, and Energy

A.J. Nolte, Ph.D., MIT
Polymers, Surface Science, Materials

I.M.B. Reizman, Ph.D., MIT
Biotechnology, Synthetic Biology

S.G. Sauer, Ph.D., Rice
Thermodynamics

A. Serbezov, Ph.D., Rochester
Adsorption, Process Control

EMERITUS FACULTY:
C.F. Abegg, Ph.D., Iowa State
R.S. Artigue, D.E., Tulane
W.B. Bowden, Ph.D., Purdue
J.A. Caskey, Ph.D., Clemson
N.E. Moore, Ph.D., Purdue

FOR INFORMATION:
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Chemical Engineering Department
Rose-Hulman Institute of Technology
Terre Haute, IN 47803-3999
Email: harwood@rose-hulman.edu
South Dakota School of Mines and Technology

Graduate Studies in Chemical and Biological Engineering

Faculty and Research Areas

Kenneth M. Benjamin (PhD, University of Michigan)
Molecular modeling, bioenergy, supercritical/ionic fluids

Timothy M. Brenza (PhD, Pennsylvania State University)
Drug delivery, nanomaterials, degradable polymers

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

Lori J. Groven (PhD, SD School of Mines and Technology)
Combustion, energetic materials, nanomaterials

Kevin R. Hadley (PhD, Vanderbilt University)
Molecular modeling, nano-materials, pedagogy

Todd J. Menkhaus (PhD, Iowa State University)
Nanotechnology, combustion synthesis, energetic materials

Jan A. Puszynski (PhD, Inst. of Chem. Tech., Czech. Rep)
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

M.S. and Ph.D. Degree Programs

Ph.D. stipends up to $32,000 per year

Students have the opportunity to use state-of-the-art research and learning spaces within the new $20MM Chemical and Biological Engineering Building. In addition many students work with well-equipped centers such as the Composites and Polymer Engineering Laboratory, CAPE, (cape.sdsmt.edu), the Engineering and Mining Experiment Station, and the Direct Write Lab. Joint collaborations exist with Biomedical Engineering, Nanoscience and Nanoengineering, Materials Engineering and Science and many other programs on and off campus.

The surrounding Black Hills provide students many opportunities to balance their academic activities with hiking, biking, skiing, snowboarding, camping, hunting, fishing, spelunking, and rock climbing.

For more information, contact Dr. Todd J. Menkhaus
Phone 605-394-2422 Email: todd.menkhaus@sdsmt.edu
Or visit: http://cbe.sdsmt.edu

SYRACUSE UNIVERSITY

BIOMEDICAL AND CHEMICAL ENGINEERING DEPARTMENT

FACULTY:
Rebecca A. Bader
Jesse Q. Bond
Katie D. Cadwell
Ruth Chen
Mandy Esch
Jeremy L. Gilbert
Julie M. Hasenwinkel
James H. Henderson
Ian Hosein
George C. Martin
Patrick T. Math
Shikha Nangia
Dacheng Ren
Ashok S. Sangani
Pranav Soman
R. Sureshkumar
Lawrence L. Tavlarides
Angela L. Zachman

RESEARCH AREAS:
Biomaterials & Tissue Engineering
Catalysis & Reaction Engineering
Complex Fluids, Soft Matter & Rheology
Corrosion & Electrochemistry
Drug Delivery
Molecular Biotechnology
Multiscale Modeling
Nanotechnology
Sustainable Energy Production
Systems Biology
Metabolic Engineering

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**TEXAS A&M UNIVERSITY — KINGSVILLE**

Wayne H. King Dept. of Chemical and Natural Gas Engineering

Chemical Engineering  
M.S. and M.Eng.  
Sustainable Energy Systems Engineering  
M.S. and M.Eng.

Natural Gas Engineering  
M.S. and M.Eng.

Ph.D.

**FACULTY**

M. L. ALEXANDER  
Ph.D., Purdue University  
Biochemical Processes, Environmental Remediation, Environmental Systems Modelling

J. A. AMAYA  
Ph.D., Texas A&M University-Kingsville  
Groundwater Management, Sustainable Processes, Simulation of Environmental Process Systems

J. L. CHISHOLM  
Ph.D., University of Oklahoma  
Reservoir Engineering and Production

H. A. DUARTE  
Ph.D., Texas A&M University  
Thermodynamics, Physical Property, Measurements, Process Simulation

P. L. MILLS  
D.Sc., Washington University in St. Louis  
Kinetics, Catalyst, and Reaction Engineering

A. L. MANRIQUEZ  
Ph.D., University of Texas-Austin  
Gas- pressure Modeling, Hydraulic Fracturing Analysis, Single and Multiphase Flow Modelling

C. D. MURPHY  
Ph.D., Carnegie Mellon, P.E.  
Process Design and Simulation

A. A. PILEHVARI  
Ph.D., University of Tulsa, P.E.  
Rheology, Oil and Gas Processing

C. XIAO  
Ph.D., University of Wyoming  
Thermodynamics, Reservoir Characterization, and Reservoir Simulation

J. S. XIE  
Ph.D., Case Western Reserve  
Biomedical Systems Engineering, Process Dynamics and Control, Thermodynamics and Heat Transfer Phenomena

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FOR INFORMATION CONTACT:  
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700 University Blvd., MSC 193  
Kingsville, Texas 78363  
(361) 593-2002 • a-pilehvari@tamuk.edu

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**VILLANOVA UNIVERSITY**

College of Engineering

Villanova University offers Master’s degree programs in Chemical Engineering and in Biochemical Engineering, and a Ph.D. program. All programs are designed to meet the needs of full-time and part-time graduate students. Funding is available to support full-time Master’s degree students.

The full-time program is research-based with research projects currently available in the following areas:

- Biomaterials and Drug Delivery Designs
- Biotechnology/Biochemical Engineering
- Systems Biology
- Supercritical Fluid Applications
- Heterogeneous Catalysis
- Biomass Resources and Conversion Technologies
- Nanomaterials
- Sustainability/Alternative Energy
- Industrial Wastewater Treatment Processes

The part-time program is designed to address the needs of both new graduates and experienced working professionals in the suburban Philadelphia region, which is rich in pharmaceutical and chemical industry. Most courses are simultaneously offered in both classroom and distance learning modes.

For more information, contact:

Dr. Vito Punzi, MSChE Graduate Program Director (vito.punzi@villanova.edu)

Dr. William Kelly, MSBChE Program Director; Ph.D. Admissions Committee (william.j.kelly@villanova.edu)

Department of Chemical Engineering • Villanova University • 800 Lancaster Avenue • Villanova, PA 19085-1681

Phone (610) 519-4950 • Fax (610) 519-7354
Research Areas
Systems and Synthetic Biology
Sustainable Energy
Biomedical Engineering
Soft Materials
Bioanalytical Devices

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.
Brian Munsky Ph.D., U. California, Santa Barbara
Christie Peebles, Ph.D., Rice U.
Ashok Prasad, Ph.D., Brandeis U.
Kenneth F. Reardon, Ph.D., Caltech
Brad Reisfeld, Ph.D., Northwestern U.
Christopher D. Snow, Ph.D., Stanford U.
Qiang (David) Wang, Ph.D., U. Wisconsin
A. Ted Watson, Ph.D., Caltech

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 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