AC 2009-29: IDEAS TO CONSIDER FOR NEW CHEMICAL ENGINEERING EDUCATORS: PART 2 (COURSES OFFERED LATER IN THE CURRICULUM)

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Ideas to Consider for New Chemical Engineering Educators: Part 2 (Courses Offered Later in the Curriculum)

Abstract

Chemical engineering faculty members are often asked to teach a core course that they have not taught before. The immediate thought is to come up with some new ideas to revolutionize that core course in ways that will engage students and maximize learning. This paper summarizes the authors' selection of the most effective, innovative approaches reported recently in the literature or discussed at previous conferences for chemical engineering courses that appear later in the curriculum, as presented at the 2007 ASEE Summer School for Chemical Engineering Faculty. The challenges associated with particular courses and solutions successfully applied to address those challenges will also be described. Courses covered in this paper include solution thermodynamics, heat and mass transfer, kinetics, and process control.

Keywords: pedagogy, faculty development

Objectives and Motivation

Although teaching is a critical mission of any college or university, today's faculty members are increasingly becoming involved in other scholarly activities. Thus, when teaching a new course, developing a good set of instructional materials can be a challenging, time-consuming task. In this paper we provide a review of some of what we consider the best practices in engineering education, applied to the following courses: solution thermodynamics, heat and mass transfer, kinetics, and process control. Note that a companion paper which covers those chemical engineering classes which normally occur earlier in the curriculum (freshmen chemical engineering, material and energy balances, fluid mechanics, introductory thermodynamics, and separations) was presented at the 2008 ASEE Annual Meeting as paper #AC 2008-1147[1].

The format used for each course is:

- Brief description of typical course content
- Discussion about novel and successful methods used, including best practices and new ideas
- Listing of "toughest concepts" for the students (and how to address them)

We further note that most of this material was originally presented by the authors at the 2007 ASEE Chemical Engineering Division Summer School in Pullman, WA[2].

Solution Thermodynamics

This course, also commonly called Thermodynamics 2, focuses on mixtures and mixture phase equilibrium as well as reaction equilibrium. Unlike the first thermodynamics course, this course normally contains exclusively chemical engineering students.

Best Practices / New Ideas

There are certain phenomena within this course that, though working against intuition, can be visualized through experimentation (both desktop and simulation). For example, some straight-forward demonstrations that can be performed to show mixture effects are as follows:

- Heat of solution – Mix salt into water and, using a thermocouple placed in the solution, have the students attempt to estimate the heat of solution
- Excess volume – Take a large, thin container and mix 500 ml of ethanol with 500 ml of water. The resulting solution is ~970 ml which demonstrates against volume additivity.
- Miscibility – One can show how the ethanol + water and the ethanol + toluene mixtures are miscible, yet toluene + water forms a miscibility gap[3].

Additionally, since changes in molecular-level interactions can manifest themselves in complicated phase behavior, simulation can be utilized to demonstrate these effects in a powerful way. One source for this information is the Etomica environment created by Kofke which houses many applets throughout the site, some of which focus on fundamental behavior germane to an undergraduate solution thermodynamics course[4].

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

- Showing exceptions to the well-known Le Chatelier's Principle[5].
- Promoting a graphical view of thermodynamics which emphasizes uncommon intuition[6] and focuses on the benefits of visualization using modern software, such as Mathcad[7]
- Falconer emphasizes the use of concept tests that use classroom response systems to allow immediate feedback from students for formal or informal assessment[8].
- A discussion on the complications of calculating liquid-liquid phase equilibrium and the potential for false solutions[9]
- An MS Excel add-in (XSEOS) to calculate a variety of thermodynamic properties using both equations of state and Gibbs excess energy models[10]
- From an experimental standpoint, a recent work describes a relatively straight-forward apparatus and modeling approach to introduce gas-liquid solubility[11]

Finally, one can utilize this class (or the previous Thermodynamics class) to provide an opportunity for students to design, price, build and demonstrate a project related to course concepts. Students are expected to keep track of their budget, set milestones, take notes to record their successes and failures, and prepare a detailed report. Industrial visitors may be interested in attending and reviewing the presentations. To promote efficiency and reuse, projects in the following year can be used to improve upon the existing design. Some example projects have demonstrated ethanol distillation through the building of a still and the appearance of miscibility gaps at different temperatures for the water and propylene glycol n-propyl ether[12].

Trouble Spots

Trouble spots for this course include:

- Often students become bogged down in the calculations and lose the big picture. Phase equilibrium calculations for mixtures (especially with equations of state) are complicated and there is a tendency to work towards finally arriving at an answer with little appreciation or interpretation of the result. Depending on the situation, the use of an Excel add-in such as XSEOS[10] or a web applet to determine phase equilibrium from an equation of state may be more appropriate[13-14]
- Reading mixture phase diagrams. By utilizing the Journal of Chemical and Engineering Data, students will find a wide variety of phase diagrams which can be used to spark discussions on Gibbs Phase Rule, Raoult's Law, miscibility gaps, etc.
- Nomenclature and symbols. In this course (and between different books), symbols have subscripts, hats, carats, superscripts, overbar, etc. A poster which describes each modification to a symbol, posted in the classroom (or prepared for the student), could be of great benefit.

Heat and Mass Transfer

The origin of heat transfer in the chemical engineering curriculum began with energy balances in the 1930's[15]. It was revitalized as a fundamental field of study through the publication of the text *Transport Phenomena*[16]. Currently, heat and mass transfer is a popular subject in the research literature.

Best Practices / New Ideas

Recent advances in simulation and modeling have allowed for a marked change in how heat and mass transfer can be taught in the classroom. There are several examples published in the literature[17-23] using computational fluid dynamics[17-19], numerical solutions[20-21], similarity solutions[22], and molecular simulations[4,23-24].

- Sinclair[17] described the use of Fluent software for use in the undergraduate curriculum. Although focused on fluid dynamics, the teaching principles illustrated in this paper can be extrapolated to heat and mass transfer courses.
- Thompson[18] used the PDE toolbox feature in Matlab to solve a variety of problems in fluid mechanics, heat transfer, and solid mechanics.
- Keith et. al.[19] used Comsol Multiphysics to illustrate how a variety of problems in fluid mechanics, heat and mass transfer, and reaction kinetics can be extended to fuel cell applications.
- Goldstein[20] solved free convection problems using similarity variables and a numerical simulation of an initial value problem.
- Binous[21] used Mathematica to solve membrane permeation problems using the complete mixing model (algebraic solution) and the cross-flow, counter-current, and co-current systems (numerical solution).

- Subramanian[22] used similarity methods for three classical problems: diffusion in a semi-infinite domain, flow past a flat plate, and the Graetz problem for flow into a rectangular channel with isothermal walls.
- Keffer et. al.[23] used molecular-level simulations to predict gas diffusivities.

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

- As mentioned previously, the Etomica environment[4,24] (www.etomica.org) provides relevant Java-based molecular simulations on its website
- Coker et. al.[25-26] describe simulation of gas separation using polymer membranes.
- Zheng and Keith[27-29] describe the use of Java applets to help students visualize heat and mass transfer.

A recent pair of papers by Flynn et. al.[30-31] focus on integrating green engineering principles into a heat transfer course. The first paper[30] describes several traditional heat transfer problems which are uniquely coupled with green engineering principles[32-33]. Example problems include: conduction shape factors and rain forest conversation, natural convection and energy-efficient lighting, natural convection through windows and life-cycle studies, radiation heat transfer for comfort and energy efficiency. The second paper[31] describes assessment of the teaching tools.

Some novel experiments in heat and mass transfer include:

- Investigation of transport of environmental pollutants in groundwater using dissolved pollutants and colloids[34]
- Experiments and modeling of lozenge dissolution to simulate drug delivery processes in the human body[35]
- Rate of drying curves and unsteady state heat transfer in cooking of french fries[36]
- Designing, building, and testing of small compact heat exchangers[37]
- Carbon dioxide loss from a carbonated beverage container[38]
- Experiments and modeling of the hemodialysis of creatinine to enhance bioengineering experiences in the chemical engineering curriculum[39]

Trouble Spots

Trouble spots for this course include:

- Students may possess weak math skills. Instructors can develop handouts to step students through difficult solution processes (such as solving differential equations). Have them practice with in-class problems and homework before testing them.
- Students may have difficulty in connecting highly theoretical content to real industrial applications – if there is an internet connected computer and projector in the classroom, instructors can use online and/or laboratory demonstrations to make a strong connection. This connection can also help students with their follow-on classes.
- Students often do not know order-of-magnitude values for heat exchanger area, mass transfer coefficients, dimensionless groups, etc. The teacher can provide

them with general values on a handout they can paste in the front of their textbook.
- Students struggle with when to eliminate terms in the governing equations. If they are provided with handouts to step them through difficult solution processes (such as solving differential equations), they will be prepared for more advanced homework and exam questions.

Kinetics and Reactor Design

The origin of kinetics and reactor design in the chemical engineering curriculum began with energy balances in the 1950's[15]. It was made available in a comprehensive form in the book by Fogler[40]. Kinetics, catalysis, reactor design and optimization all remain a popular subject in the research literature.

Best Practices / New Ideas

Recent advances in simulation and modeling are not limited to problems in transport phenomena. There are several examples published in the recent educational literature[41-47] which will now be summarized.

- Stochastic simulations of chemical reactions[41-42.] Martinez-Urreaga et. al.[41] used MATLAB to simulate the reversible reaction A ↔ B, while Fan et. al.[42] simulated the thermal death kinetics of a cell population.
- Computational fluid dynamics[43-44]. Lawrence et. al.[43] used CFX commercial software to incorporated non-ideal reactors into the curriculum. They developed residence time distributions in tubular reactors and used them to determine conversion for a reaction using Langmuir-Hinshelwood kinetics. Madiera et. al.[44] simulated a complex two-dimensional reservoir and determined the residence time distribution and predicted the conversion during steady-state operation.
- Parulekar[45] used Mathcad to perform numerical simulations of several fundamental kinetics and reactor design problems, including estimation of kinetic parameters, autocatalytic reaction and space times for operation of continuous and plug-flow reactors, gas phase sulfur dioxide reaction to sulfur trioxide, predicting equilibrium composition of a reaction mixture, steady-state multiplicity in continuous reactors, membrane reactors, series-parallel reactions, and consecutive reactions.
- Wilcox[46] described the utility of computational quantum chemistry for solving advanced problems such as the development of rate expressions from transition state theory.

An excellent paper by Muske and Myers[47] integrates principles of statistics and experimental design into a project to determine the forward and reverse reaction kinetic rate constants for ethylene hydrolysis into ethanol. Complicating the problem is that students need to determine the Arrhenius parameters for these reactions. Students are given a budget and request "experimental" runs from which they are supplied data by email one day after their request. A process simulation with statistical fluctuations is used to generate results and mimic a real experimental study. They must decide when they have enough data (or when they run out of money), and possibly adjust their experimental plan in order to perform the analysis.

The Safety and Chemical Engineering Education (SACHE) program is a joint effort between the American Institute of Chemical Engineers Center for Chemical Process Safety and academic institutions. Founded in 1992, the committee typically organizes a yearly workshop to educate chemical engineering faculty on the importance of safety education. Their website[48] features problem sets and web modules that can be used in the classroom. It is noted that some features of the site require a password for access. An example module is the Chemical Reactivity Hazards Instructional Module49 developed by Robert Johnson of Unwin, Co. The module can be used to motivate the importance of safety in kinetics and reaction engineering. It highlights several major incidents where uncontrolled chemical reactions can result in devastating consequences. Additional safety material is available in Crowl and Louvar's textbook[50].

Laboratory experiments in kinetics and reactor design include:

- Hesketh et. al.[51] developed an experiment to explore the heterogeneous reaction of propane in an automobile catalytic converter. The students measure the compounds exiting the converter using Fourier transform infrared spectroscopy. Furthermore, a simple model is used to fit the experimental data to determine reaction rate parameters.
- Shonnard et. al.[52] developed a batch fermentation experiment to produce l-lysine in the senior laboratory. The students in the lab each perform an experiment that is part of a larger factorial design matrix. The students then share data and analyze all of the results.
- Li et. al.[53] developed an experiment to study the growth of yeast in a small scale bioreactor. Students measured the concentration of yeast cells and glucose, and after learning about biological reaction kinetics, they can estimate the doubling time for the yeast.
- Dahm et. al.[54] developed a set of micromixing experiments to use in the undergraduate reaction engineering course. In a lecture on micromixing, the students are taught about the perfectly mixed and totally segregated reactor models. Experiments were performed on a system with parallel competitive reactions in a 2 L reactor with baffles and a mixer, and also in a 600 mL beaker with a magnetic stir bar. Results show that the selectivity is higher in the baffled reactor.
- Rice et. al.[55] developed an experiment for propane hydrogenolysis on an alumina supported platinum catalyst. Students run the reactor to obtain power law kinetic parameters (to determine reaction order in propane and hydrogen) as well as Arrhenius parameters.

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

- Dartmouth University has an online JAVA periodic table[56] which contains puzzles and quizzes and a molar mass calculator. The same group has a JAVA kinetics plotter[57] which can be used to fit zero, first, or second order kinetics to supplied experimental data.

- The University of California at Irvine has a JAVA applet to simulate molecular motion, collision, and reaction[58]. The user enters initial concentration of red, yellow, green, and blue molecules. Upon the interaction of a red and yellow molecule, a green and blue molecule are formed. The reaction is reversible, and the user can enter the forward and reverse reaction rate constants.

Trouble Spots

Trouble spots for this course include:

- Students may possess weak math skills. Instructors can develop handouts to step students through difficult solution processes (such as solving differential equations). Have them practice with in-class problems and homework before testing them.
- Students may have difficulty recalling material from previous courses that may be considered prerequisites for a kinetics and reaction engineering course. Recalling fundamental chemistry, especially organic chemistry, can be difficult for even advanced students. The instructor can summarize some of the important reactions to aid students in feeling comfortable in an upper level course.
- Students often do not know order-of-magnitude values for reactor volumes or pressure drops. The teacher can provide them with general values on a handout they can paste in the front of their textbook.
- Students do not know many of the assumptions in the basic reactor models (batch, continuous stirred tank reactor, plug flow reactor) and how valid they are in laboratory or industrial applications.

Process Control

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

Best Practices / New Ideas

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

A recent article published by the International Society of Automation magazine *InTech* reported on the views of prominent chemical engineers regarding the role of process control instruction[59].

- Douglas Cooper (University of Connecticut, Control Station, and ControlGuru.com) suggested that the course provide a “practical skill set… including enough theory to excite those destined for graduate study”
- Cecil Smith (formerly of LSU and currently a consultant) suggested “We teach fundamental principles, but include only theory relevant to engineering practice”

and “Focus on basic regulatory control, and do it well. Leave optimization, model predictive control, etc. to subsequent courses and advanced degree programs.”

- Jim Riggs (Texas Tech and author of *Chemical and Bio-Process Control*[60]) stated “This is the classic question of theory versus practice in engineering education. The key to this problem is to provide control courses that provide basic industrially relevant skills while also providing a fundamental understanding of process control and process dynamics”

Riggs also states that the course should teach students to:

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

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

Tom Edgar (University of Texas at Austin and co-author of the textbook *Process Dynamics and Control*) suggests[61]:

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

A thorough discussion of the question of what to teach in process control was recently published[62].

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

- Moor and Piergiovanni[63] used small modular kits and Control Station
- Silverstein[64] used unit operations scale apparatus and MATLAB/Simulink
- Henry[65] uses simulation and remote experiments on batch distillation

Additional laboratory ideas include:

- Young et. al.[66] developed a nonlinear, MIMO salt mixing process control laboratory experiment
- Rusli et al.[67] used multivariable control for a quadruple-tank process control experiment.

- Long et. al.[68] suggest experiments on air pressure tank systems
- Muske[69] uses a simple tank in a process control laboratory

Web resources include:

- McMaster University[70] hosts a web page including numerous resources for teaching controls
- Henry[71] has a number of remote laboratories available online

Software resources include:

- Loop-Pro Trainer[72]
- MATLAB with Simulink[73], an add-on which uses the same block notation used in most texts
- A numerical approach with Microsoft Excel®[74]
- Excel/VBA based simulation[75]

Trouble Spots

Trouble spots for this course can include:

- Students not understanding the physical meaning of the Laplace variable "s". This will likely remain a mystery. Instead, focus on how conservation laws in the Laplace domain can be arranged to yield key information about process behaviors through parameters like gains and time constants.
- Bringing in computing tools too early or too late. Students must understand the how and why before actively developing models with software like Simulink. The appropriate time to introduce them will depend on your curriculum, but probably should be after students have mastered modeling fundamentals and can at least handle simple Laplace domain solutions for open- and closed-loop systems by hand. Some simulation tools, like Loop-Pro[72], can be used for inductive instruction on principles of control without requiring significant mathematical analysis.
- Losing sight of practical control. Better control can always be obtained—at a cost. Students must continually be reminded that there is always an optimal level of control, dependent on the cost to implement control versus marginal profit from enhanced control. The roles of safety and environmental protection should also be considered.

Use of Active Learning

The authors are all advocates of using active learning within their courses. As such, a brief background and listing of simple ideas on how to integrate active learning into a core chemical engineering course has been provided by the authors[1] and is summarized here.

- Active learning is underscored in teaching textbooks[76-77] and those intended for the new professor[78-79] as well as in numerous conference proceedings and engineering education archival publications and conference proceedings.

- Active learning is presented at the National Effective Teaching Institute (NETI)[80] and the Excellence in Engineering Education (ExcEEd)[81] workshops.
- Game-based active learning exercises increase active learning in the classroom (for examples, see references 79, 82-83)

Other simple-to-use active learning methods include:

- Think-pair-share – think for 1-2 minutes, talk with neighbor for 1-2 minutes, then share answers with the rest of the class)
- Poll the audience – with a show of hands, colored notecards, or clickers
- Minute paper – the students write down 1-2 ways to do something, then the instructor solicits answers from the students. This is also a good way to get anonymous feedback on the course content, what the "muddiest" point of a lecture is, etc.
- Engineering Education articles from Rich Felder[84] – this site highlights recent teaching methods that have been proven to improve student learning

Conclusions

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

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

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