Class and Home Problems (CHP) present scenarios that enhance the teaching of chemical engineering at the undergraduate or graduate level. Submissions must have clear learning objectives. CHP papers present new applications or adaptations that facilitate learning in specific ChE courses. Submit CHP papers through https://journals.flvc.org/cee, include CHP in the title, and specify CHP as the article type.

INCORPORATING INCLUSIVITY AND ETHICAL AWARENESS INTO CHEMICAL REACTION ENGINEERING

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INTRODUCTION

With the advance of engineering education research and scholarship, there has been an increased focus on amending chemical engineering courses to increase student learning, engagement and enjoyment. These approaches are often incorporated in project-based courses such as capstone design courses and laboratory courses, providing opportunities to apply knowledge to authentic problems that increase student learning and enjoyment. There has also been increased interest in the integration of active pedagogies into core chemical engineering courses, such as flipped classrooms, screencasts, or conceptual clicker questions.[1–3]

The Chemical Reaction Engineering (CRE) course at the University of Michigan has had a long-standing tradition of advancing student-centered learning techniques. With the use of his textbooks,[4,5] Professor Scott Fogler introduced the use of the CRE algorithm that helps students solve CRE problems through critical thinking rather than memorization. Students are tasked with applying it to a range of industrially-relevant processes as well as other real world processes such as modeling hippopotamus digestive processes as standard CRE reactors. Professor Fogler also implemented the use of In-Class Problems (ICPs) into lectures. The in-class time for the CRE course is structured as two hours, two days a week. One-and-a-half hours of class is devoted to traditional lecture (incorporating other active learning elements, such as clicker questions) and a half hour is devoted to ICPs. During the ICPs, students work in teams of three or four to solve an assigned problem. Approximately four facilitators (the instructor, graduate teaching assistants and/or undergraduate teaching assistants) walk around the classroom to assist students with problem-solving. With this structure, students benefit from working on problems both with each other and with the teaching team.

ICPs provide many benefits for student learning, engagement and enjoyment. The clearest benefit is providing a source of active learning for the students. Active learning, in which students are engaged in their own learning rather than passively listening to lectures, helps improve student motivation, understanding and enjoyment.[6] Using In-Class Problems

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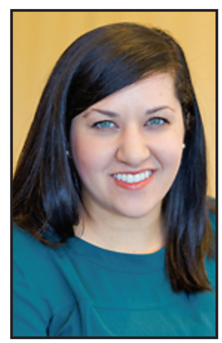

Heather Mayes *is an Assistant Professor in the Department of Chemical Engineering at the University of Michigan. Her research group uses computational approaches, including multiscale modeling and transition path sampling, to discover protein-sugar interactions and reaction mechanisms, such as how enzymes break down or build polysaccharides. The resulting insight can be used for enzyme rational design to harness carbohydrates for renewable materials and improved health. She collaborates with experimental groups to understand past and guide future wet-lab studies to advance biotechnology and understanding of glycobiology.*

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encourages students to self-direct their own learning backed by the assistance of instructors and facilitators. Students also benefit from working with their peers on problem-solving teams.[7] Students of all abilities benefit from working with others: students with higher conceptual understanding improve their understanding by explaining the material, whereas students who may be underperforming are able to learn from their higher-performing peers.[8] Students working in teams are also able to complete more challenging problems than they could do on their own. Students also benefit socially by making connections with their peers. These connections also help to strengthen students' sense of community within their class, or more broadly, within their major or college. Finally, the ICPs serve to allow the teaching team to closely gauge how well the class understands new material, which in turn enables the instructors to structure the coursework to better address students' needs, misconceptions and interests; in other words, to make class problems more inclusive.

Inclusive teaching is important in order to ensure that *all* students – in particular, underrepresented engineering students (women and underrepresented minorities) – have equitable opportunities for learning in the classroom. By making the classroom a better place for underrepresented students, all students benefit.[9] Inclusive teaching encompasses utilizing pedagogical techniques that reach a wider variety of students with different backgrounds and supporting student teams so all students can have a positive team experience.[10,11] One specific way to make the classroom more inclusive can be to focus on engineering ethical considerations: the discussion of social or ethical considerations better serves underrepresented students who are more clearly impacted by social dynamics. Incorporating work that has clear social implications has been shown to improve underrepresented student engagement in the classroom.[12,13] Furthermore, a study found that student interest in public welfare *decreases* over their time in engineering programs,[14,15] which could be due to a lack of discussion of social issues or ethical considerations in engineering courses; thus, incorporating more problems that focus on ethics can also address this issue.

In the case of the CRE course at the University of Michigan, recent efforts to make the course more inclusive have involved developing new types of problems for ICPs, homework, and exams that include a wider variety of student interests and address student learning in different ways. This paper presents some of the problems recently developed for the CRE course. They incorporate diverse "real world" applications that intend to reach a wider variety of student interests and several focus specifically on engineering ethical considerations.

INCORPORATING DIVERSE REAL WORLD APPLICATIONS

There has been more effort to tie in a wider variety of real world applications throughout the course, in lectures, homework assignments, exams, and In-Class Problems. By consistently relating CRE concepts to current events or issues, students see the relevance of the course material and are able to link the concepts to their own experiences. The real world applications chosen also include a variety of topics so that different students can have examples that appeal to them and encourage their interest in the course. This is especially useful for students who have had less exposure to engineering in the past. Students who have had parents who are chemical engineers, for example, already have a perception of engineering and may know how the career path can fit into their life goals and interests, while students who have had less exposure to chemical engineering can benefit from seeing a wider variety of applications of the material, so they can determine how they want to shape their chemical engineering career. Below, four new real world CRE problems are presented. Solutions can be provided to instructors upon request via email to Heather Mayes (hbmayes@umich.edu).

Kinetics in a Diamond Ring

As at many universities, chemical engineering students at the University of Michigan take thermodynamics before taking CRE (or kinetics), so we often discuss when thermodynamics principles (versus kinetics) dictate results. We use this knowledge to scaffold a particularly challenging concept for students: the range of valid rates and rate coefficients. Many chemistry labs utilize reactions with timescales on the order of minutes at near ambient conditions, as is appropriate for the constraint of class time. In CRE, we also discuss real world reactions that take days or more, such as the fermentation of sugars. To expand students' range of valid time scales, we refer to the carbon phase diagram, which most students have seen by the time that they take CRE. The students quickly recognize that the diagram shows that graphite is the most stable form for carbon at ambient conditions, but when asked whether they should worry about a diamond ring becoming the basis for a pencil, they know that the answer is no. They approximate the timescale for the transformation at room temperature by calculating the inverse of k (the rate coefficient) at 25°C, given that the activation energy is 253 kcal/mol (from measurements at high temperature[16]) and a pre-exponential factor (A) of 6.2×10^{12} 1/seconds (from transition state theory calculated at 25°C). The approximate timescale of 6×10^{172} seconds (2×10^{165} years), even if off by several orders of magnitude, helps the students comprehend that the diamond on the ring is a powerful symbol of the importance of kinetics (while perhaps only coincidentally also representing a long-timescale marriage).

Maillard Reactions in Baking

Another way to introduce chemical reactions in a real world setting is within the context of cooking or baking. While food bakes, chemical reactions are occurring that must be controlled by baking for a certain time or at a certain temperature. In the first midterm, the problem below introduces the

Maillard reaction, which is a series of reactions that causes browning as food cooks or bakes.

The delicious browning conferred by baking, roasting, and grilling is due to a complex set of reactions between proteins and sugars called Maillard reactions. One such reaction occurs between glucose and proline to form products including 2-acetylfuran, which we will model as the irreversible, liquid-phase reaction:

glucose + proline →2-acetylfuran + other

Experiments have found that this reaction is zero-order both in glucose and proline and has an activation energy of 18 kcal/mol. If your signature dish takes 40 minutes to roast to perfection at 300 °F (149 °C), how long would it take to reach the same conversion of this reaction at 275 °F (135 °C)?

In the second midterm, the problem was expanded from considering one reaction to considering three. By continuing a problem from the first midterm, students also see how the material in the class builds upon itself. Instead of seeing class topics as separate, compartmentalized units, students are able to see how they relate. In addition to completing typical CRE calculations related to these reactions (determining yield, selectivity, etc.), students were also asked a question that related the reactions to taste preference, solidifying the "real world" connection to CRE even more.

We know that the delicious browning conferred by baking, roasting, and grilling is due to a complex set of reactions between proteins and sugars called Maillard reactions. On the first midterm, we assumed that only one reaction occurred. Now, we will analyze 3 simultaneous, irreversible, liquid-phase, zero-order reactions.

If you prefer the taste of your dish when roasting it at 275 °F for 83 minutes instead of the original recipe (300 °F for 40 min), why might that be?

FOCUSING ON ENGINEERING ETHICAL CONSIDERATIONS

Incorporating more diverse real world examples can serve to reach a wider variety of students. Students can be even better served by incorporating problems that address the consideration of engineering ethics, such as social or environmental impact.

Flame Retardants

This ICP is another popular one among students and has been adapted from a problem in the textbook *Elements of Chemical Reaction Engineering*.[5] Students investigate how flame retardant compounds work, calculating the net rates of formation of various compounds and determining how these rates of formation are impacted by the presence or absence of flame retardants.

Flame retardants added to fabric have saved many lives, yet are controversial because the chlorinated or brominated compounds can also be detrimental to human health and the environment. Let's understand why these compounds are used. Hydrogen radicals are important to sustaining combustion reactions. Consequently, if chemical compounds that can scavenge the hydrogen radicals are introduced, the flames can be extinguished.

This ICP again reinforces the topic of safety. It also serves as a discussion point for a controversial topic – if the utility of flame retardant materials outweighs the negative environmental effects – thus encouraging students' critical thinking within the context of a real world scenario.

This topic continues on a subsequent homework problem, where students were tasked with considering the ethical considerations of flame retardants:

You have now investigated the basic mechanism by which flame retardants work. Multiple chemicals are used for this process and mandated to be included in specific clothing (e.g. children's sleepwear) and furniture (e.g. foam in couches). However, these laws and practices are controversial. Find an article that describes the controversy. Cite and summarize it here.

Less-Toxic Antifreeze

A problem on the final exam involved students developing a non-toxic antifreeze.

Ethylene glycol is used as antifreeze, such as in windshield fluid to remain liquid during Michigan winters, but is also toxic. Propylene glycol ("G") is also an antifreeze, but is non-toxic. Thus, you want to engineer production of propylene glycol given the data/constraints listed below. Propylene glycol is formed from the reaction of propylene oxide ("X") and water ("W"), with a small amount (0.1 wt%) of sulfuric acid (H_2SO_4) that acts as a homogeneous catalyst (Figure 1), where:

$$k_1(T) = 1.7\ x\ 10^{11} exp\left(\frac{-9000K}{T}\right)\frac{L}{mol \cdot hr} \tag{1}$$

$$\Delta H^{\circ}_{Rxn1} = -85\ kJ/mol \tag{2}$$

Your fellow intern recommends that you add methanol ("M") as an inert to the feed. However, you checked reference books and found that it reacts with propylene oxide ("X") as shown below, creating either a primary alcohol ("P") or a secondary alcohol ("S") (Figure 2), where:

$$k_2(T) = 5.8\ x\ 10^{10} exp\left(\frac{-9000K}{T}\right)\frac{L}{mol \cdot hr} \tag{3}$$

$$\Delta H^{\circ}_{Rxn2} = -48\ kJ/mol \tag{4}$$

$$k_3(T) \approx k_2(T) \tag{5}$$

$$\Delta H^{\circ}_{Rxn3} \approx \Delta H^{\circ}_{Rxn2} \tag{6}$$

Assume all reactions shown follow elementary rate laws. Additional properties are reported below. Production will use a CSTR with the following operating conditions (Figure 3).

This problem statement contains sufficient information for a multi-part question, asking students to do various calcula

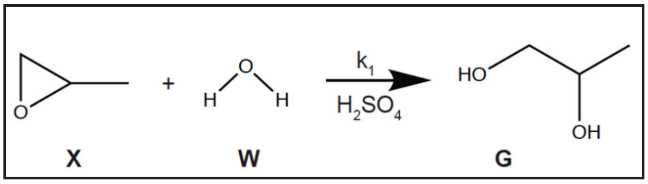

Figure 1. *Reaction to create propylene glycol.*

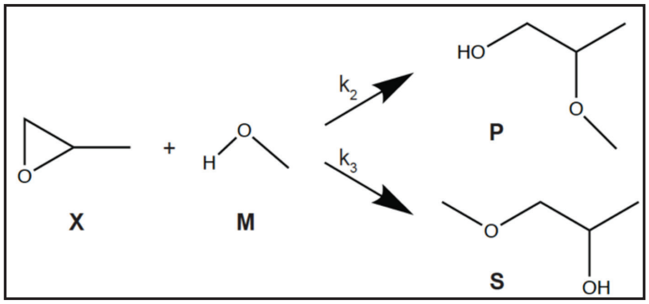

Figure 2. *Reaction creating a primary or secondary alcohol.*

$$T_0 = 27\ ^\circ\text{C}$$
$$\nu_0 = 6000\ \text{L/hr}$$
$$F_{X0} = 20\ \text{kmol/hr}$$
$$F_{W0} = 200\ \text{kmol/hr}$$
$$F_{M0} = 25\ \text{kmol/hr}$$
$$V_{\text{CSTR}} = 350\ \text{L}$$

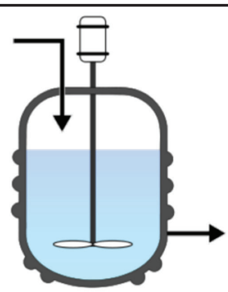

Figure 3. *CSTR and operating conditions. Heat capacities are as follows: $C_{P,X}$=125 J/mol K, : $C_{P,W}$=70 J/mol K, : $C_{P,M}$=80 J/mol K, and : $C_{P,G}$=$C_{P,P}$=$C_{P,S}$=180 J/mol K. Assume all heat capacities are independent of temperature.*

tions, including the maximum cooling rate from the jacket, analysis of multiple steady states, and calculation of selectivity. Importantly, after calculating these quantities, it asks:

> *Do you agree that adding methanol to the feed is a good idea? Why?*

From the beginning of the problem, students are considering real world experiences; as students in the Midwest taking this class during the winter, they are familiar with the need for products that can withstand the cold, and may have heard about the toxicity of ethylene glycol used as antifreeze in products such as windshield-wiper fluid. The final question ("do you agree…") is an open-ended question that allows the students to bring together multiple considerations. In the problem, they calculated heat-capacity of the added methanol and the undesired products that are created, reducing the selectivity of the desired product. Finally, if students have practiced considering health and environmental considerations of different solvents, they can bring that knowledge in as well, deciding that the toxicity of methanol and the reduction in selectivity are not worth the slightly higher heat capacity of methanol versus water.

Flint Water Crisis

Another real world problem that hits, quite literally, close to home was considering the contaminated water in Flint, Michigan. In class, there was a discussion of "pre-flushing" and why this is a recommended strategy when having contaminated water; on the homework, students were tasked with continuing to consider this strategy.

> *"Pre-flushing" came up in discussions of the Flint water crisis. This refers to running water for a period of time (usually a few minutes) before taking a sample. We will use our knowledge of reaction engineering to help us understand the difference in the concentrations of chemical species in water right when a faucet is open (no pre-flushing) versus after flushing water for several minutes. While many reactions are possible, we will consider just one reaction (Equation 7):*

$$Fe\ (II) +\ O_2 \rightarrow Fe(III) +\ O_2^- \tag{7}$$

> *This reaction is applicable to the Flint Water Crisis because almost all homes there were built before a ban on lead solder. Lead from this solder would enter the water as rusted galvanized iron pipes corroded in the presence of chloride (commonly used as a disinfectant in municipal water supplies), dissolved organic material, and phosphate. In Flint, the amount of chloride present was four times higher than the threshold used to predict accelerated galvanic lead corrosion, and phosphate was approximately three times the minimum reporting level.[17] The reaction above is a pseudo-first-order reaction depending only on the concentration of Fe(II) ions in the water. Under these conditions, in tap water at pH 6.5 and room temperature (~21 °C), the pseudo-first-order rate coefficient is 0.0085 min^{-1}. A reasonable estimate for home plumbing is 1" internal diameter and 100 feet between the city water main and the faucet outlet.*

a. *Write the rate law for this reaction.*

b. *How would you model the reactions in a pipe when there is no flow (valves closed), as is often the case overnight? How would you model the reactions in a pipe when the valves are open and there is a steady outlet rate, as when a faucet is open?*

c. *For an initial Fe(II) ion concentration of 5.37×10^{-5} M in the pipe with no flow (valves closed), what is the concentration of Fe(III) after 10 hours?*

d. *An estimate for the volumetric flow through a faucet is 16 gallons/min. If the Fe(II) inlet concentration (from the city main) is 5.37×10^{-5} M, what is the concentration of Fe(III) at the outlet of the faucet?*

e. *As discussed in our book and in class, spacetime ($\tau = V / v_0$) gives us an estimate of the time it takes for a fluid (i.e. fresh water from the city water main) to move through the whole length of the pipe. Calculate τ for the pipe.*

f. Coming back to our original question, why would it make a difference if a sample is tested right after turning on a faucet after a period of disuse, as in first thing in the morning, versus after "flushing" for several minutes?

g. Several years ago, I participated in a tour of a water treatment facility (recommended activity). The engineers working there (mostly ChemEs) recommended consuming water in the morning only after using it for other purposes, for example, taking a shower before using tap water to make coffee. Do you agree with their advice?

This question requires critical thinking, relates to a real environmental problem, and has applications in day-to-day life. This was a favorite problem of students.

CONCLUSION

The Chemical Reaction Engineering (CRE) undergraduate course at the University of Michigan has long had a tradition of incorporating thoughtful pedagogy and active learning to improve the student experience. More recently, extra efforts have been made to improve the class in order to make it even more inclusive, by incorporating more discussion of engineering ethical considerations and focusing problems on a variety of real world topics. Including discussion of social and environmental considerations instills the importance of considering engineering ethics, further links students' conceptions of the material to the real world, and provides the opportunity to better reach underrepresented students. Utilizing diverse real world examples throughout the class problems engages a diverse set students with the material and shows students how they can apply CRE theory to any career path that they wish to pursue.

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