THE CHEMICAL ENGINEERING BEHIND HOW POP GOES FLAT:
A Hands-On Experiment for Freshmen

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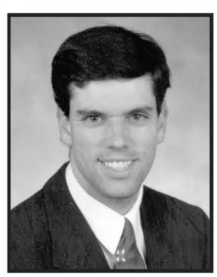
One of the endemic problems specifically in chemical engineering, as well as in the field of engineering in general, is the low retention rate of undergraduate students. This attrition is especially noticeable in the first two years of undergraduate studies, as roughly 50% of freshmen entering chemical engineering do not make it to their senior year.[1] While students have varying reasons for transferring out of science and engineering fields, one of the most common is a loss of interest in science and engineering.[2] In most chemical engineering departments, students do not take a core chemical engineering course until their sophomore year, and don't become immersed in chemical engineering until their junior year. This means that underclassmen who switch majors due to a loss of interest in science and engineering do so without a good understanding of chemical engineering.

To combat the retention problem, many chemical engineering departments require an introductory course in chemical engineering during the first semester of the freshman year. Typically these courses serve to introduce students to the department and its procedures, and give a broad overview of some applications in chemical engineering. From a brief survey of course descriptions and syllabi found on the Internet, it appears that many of these courses use field trips to chemical plants and presentations by guest speakers to give students more of a perspective on the discipline. While these are excellent activities to which students in chemical engineering can be exposed, one problem is that they are,



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for the most part, passive activities. Students are generally hearing someone tell them what chemical engineering is or are seeing pieces of process or laboratory equipment. They are not touching, designing, or building anything. Hands-on activities are relatively rare, though some departments have used them successfully.[3-7]

There are numerous reasons why hands-on projects are not incorporated into freshman chemical engineering courses more often. First of all, freshmen do not generally have the background to apply many chemical engineering principles. Secondly, it is difficult to package a true chemical engineering application into something that freshman students can manipulate since chemical engineering frequently deals with very large and sometimes hazardous processes. Finally, many interesting activities would require extensive laboratory and calculational time (on the order of the laboratory experiments taught in chemical engineering lab courses). The requirement for a useful hands-on activity that could be incorporated into a freshman course is one that is interesting, safe, easily understood by students with limited chemical engineering knowledge, fairly simple, and capable of being completed in a reasonable amount of time. This paper details such an experiment that in fall 2003 and fall 2004 was incorporated into a freshman chemical engineering course at Kansas State University (CHE 110, Current Topics in Chemical Engineering). This experiment has students study the often-encountered phenomenon of carbonated soft drinks that have lost their fizz (here in Kansas, we call that flat pop). Students design and carry out experiments to study one aspect of this phenomenon. The efficacy of this exercise in teaching students what chemical engineering is and in increasing student enthusiasm for studying chemical engineering was measured by a semester-end survey.

BACKGROUND

Freshman students are generally familiar with the phenomenon of carbonated beverages going flat, and have some intuitive understanding as to why it occurs. Most will know that the loss of carbonation leads to a flat beverage, and some will recognize that carbonation is simply the absorption of CO_2 into the liquid phase. What students will not be familiar with are the chemical engineering principles behind how pop goes flat and how chemical engineers use many of these principles to design chemical processes.

There are numerous chemical engineering principles involved in the loss of carbonation. This is truly a rich mass-transfer problem. Loss of carbonation depends on two factors: the gas-liquid equilibrium for CO_2 and the rate at which mass transfer of CO_2 from the liquid to the gas phase occurs. The gas-liquid equilibrium is represented by Henry's Law:[8]

$$H = P_{CO_2}(g) / C_{CO_2}(l) \qquad (1)$$

where $P_{CO_2}(g)$ is the CO_2 partial pressure in the gas phase, $C_{CO_2}(l)$ is the concentration of CO_2 in the liquid phase, and H is the Henry's Law constant.

Given enough time, CO_2 will leave the liquid solution and enter the gas phase until the above equilibrium relationship is fulfilled. Temperature plays an important role, as the Henry's Law constant decreases with increasing temperature. For carbonated beverage bottles left closed for long periods of time, equilibrium is the most important factor in how the carbonated beverage goes flat. The volume of the head space is clearly important here, as the partial pressure in the entire volume must satisfy the equilibrium relationship. Large head space volumes lead to a large loss of CO_2 from the liquid.

Mass transfer kinetics can be important in such situations. There really are two types of mass transfer occurring in this system: mass transfer of CO_2 from the liquid to the gas and mass transfer of CO_2 through the bottle to the outside atmosphere. For the standard polymer used to construct carbonated beverage bottles, polyethylene terephthalate, the rate of mass transfer of CO_2 through the bottle is small. This would not be the case, for instance, if low-density polyethylene was used to make the bottle. The rate of mass transfer from the liquid to the gas becomes important in loss of carbonation if the bottle is opened and closed often within a short period of time. In this case, there is not enough time to reach equilibrium, so the CO_2 lost from the liquid phase is the amount that went into the gas phase in the time between openings. Mass transfer of CO_2 into the gas phase can be represented by:[8]

$$N_{CO_2} = K_G (P_{CO_2} - P_{CO_2}{}^*) \qquad (2)$$

where:

$$P_{CO_2}{}^* = HC_{CO_2} \qquad (3)$$

N_{CO_2} is the flux of C_{CO_2}, P_{CO_2} is the partial pressure of CO_2 in the gas phase, K_G is the gas-phase mass transfer coefficient times the mass transfer area, $P_{CO_2}{}^*$ is the partial pressure of CO_2 at the gas-liquid interface, and C_{CO_2} is the concentration of CO_2 in the bulk liquid.

IMPLEMENTATION

This activity was incorporated in CHE 110 (Current Topics in Chemical Engineering) for fall 2003 and 2004. This is a one-hour introductory chemical engineering course that freshmen and transfer students are required to take for a letter grade. Four of the 16 contact hours were spent on the CO_2 absorption activity. The remaining time was dedicated to lectures on curriculum requirements, advising and enrollment, how to seek internships and full-time positions, applications of chemical engineering, and field trips to a dairy processing facility and the chemical engineering laboratories.

Students were presented with the topic of carbonated beverages going flat by having a number of students take the "Pepsi challenge," in which they sampled two different beverages and determined which tasted better. To show why carbonation is important, one of the beverages was flat while the other was fresh. Brief discussion of what made the fresh beverage better ensued. This was followed by a discussion of why carbonated beverages go flat, which introduced the idea of CO_2 absorption and set up a discussion of mass transfer and gas/liquid equilibrium.

Students were then shown two ways to quantify the mass transfer of CO_2 from carbonated beverages. The first method was based on an article by Crossno.[9] Briefly, a balloon filled with 50 ml of 1M NaOH was affixed to a flask containing 150 ml of a carbonated beverage. The beverage was stirred and left for ~24 hours to drive the CO_2 out of solution. CO_2 was adsorbed into the sodium hydroxide solution to form sodium carbonate. Titration of that solution to the first colorless phenolphthalein endpoint neutralized the excess sodium hydroxide and converted all of the sodium carbonate to sodium bicarbonate. Continuation of the titration to the methyl orange endpoint converted the sodium bicarbonate to water and CO_2. The amount of HCl required to go from the phenolphthalein endpoint to the methyl orange endpoint gave the amount of CO_2 in the carbonated beverage.

The second method was to replace the original bottle cap with a cap in which a pressure gauge had been placed. This cap allowed the pressure in the head space to be measured as a function of time.

During demonstration of the two methods, laboratory safety procedures were highlighted and a handout was given on these procedures. Following the demonstrations, the students were told to form groups (self-selected) of four or five students. Each group was told that they were to identify and select one research topic related to the mass transfer of CO_2 in carbonated beverages. Several topics were suggested to them, although they were encouraged to brainstorm their own project ideas. They were then instructed to identify what experiments and measurements they needed to do in order to address the research question. They were finally told that they would be required to report their results in both a written and an oral report. Final written reports were turned in the last day of class. Oral reports were given during class time in front of the whole class in the last two or three weeks of the class.

Performance on the project was a major factor in the students' final grade. In the first year of implementation, an overall letter grade was assigned for the reports, which was given roughly equal weight with attendance. In the second year of implementation, the project was assigned 200 points out of a possible 500 points, with the remainder of the points for attendance. Students were required to turn in several reports during the semester to ensure that they were making progress on the project. The reports and their point value are as follows: firing memo (described in the following paragraph), 10 points; description of experimental objectives, 10 points; detailed experimental plan, 20 points; preliminary results report, 20 points; rough draft of final report, 10 points; final written report, 100 points; oral report, 30 points.

The students were given little information on working in teams the first year, and this led to a few problems (described in the results section). To address this problem in 2004, each team was asked to meet and discuss the team's expectations for individual team members. They were also asked to lay out what specific actions would be taken if students did not meet those expectations, leading up to a possible ultimate action of "firing" the individual. They were then required to write a document (a "firing memo") detailing this discussion and all team members had to sign it. In addition, students were required to rate their peers in a number of areas, such as attendance at team meetings, contribution to reports, and attitude, and turn in their ratings with the final report. Students consistently rated low by their peers received a deduction of their project grade, with the severity of the deduction determined by how low their ratings were.

RESULTS

Because students were allowed to choose their own research topics, topic selection varied. Topics included:

- *Does the commercially available Fizzkeeper work?*
- *How does temperature affect CO_2 absorption?*
- *Estimate the mass transfer coefficient for CO_2 loss from carbonated beverages.*
- *Estimate Henry's Law constant for CO_2 in carbonated beverages.*
- *Determine effect of different container materials (polyethylene, glass, and PET) on carbonated beverages going flat.*
- *Determine how different PET beverage containers affected the loss of CO_2 over time.*
- *How does the length of time the cap is left off a bottle affect the rate at which the carbonated beverage goes flat?*

The experiments the students conducted and how they analyzed their data varied for the different projects. Most groups addressed their research question empirically. For example, several groups plotted CO_2 concentration and/or gas pressure vs. time for different conditions (*i.e.*, different temperatures, with and without a fizzkeeper). These groups did not use the mass transfer equations described above.

Other groups relied on the mass transfer equations to address quantitative questions, such as estimating the Henry's Law constant or the mass transfer coefficient. The group that estimated the Henry's Law constant measured concentration of CO_2 in the liquid phase and pressure in the gas phase for several different samples, and attempted to fit these data with a single value of the Henry's Law constant. The group that attempted to estimate a mass transfer coefficient measured the gas pressure over time after the bottle had been opened and closed (to start with atmospheric pressure). From the known volume in the head space and the measured pressures, they could calculate the change in moles of CO_2 in the gas phase. Next, the students solved Eq. (2) by separation of variables, assuming that the concentration of the liquid (and therefore $P_{CO_2}*$) was a constant over time at the value they measured after the mass transfer experiment. They then plotted their experimental data using the resulting equation, and found K_G from this plot. Essentially, they plotted the logarithm of the partial pressure vs. time, which yielded a linear plot, the slope of which was K_G. This analysis assumed that all of the mass transfer resistance was in the gas phase, which likely was not the case. Making this assumption helped in the analysis, however, since the students could readily measure the gas-phase pressure over time.

The titration procedure was problematic for some students. Sometimes students found that the balloon containing NaOH, in which CO_2 was absorbed, had been sucked into the flask when they returned to the laboratory for titration. Sub-atmospheric pressures had apparently been created inside the balloon due to loss of CO_2 from the gas phase, causing the balloon to shrink and eventually completely collapse. Students also reported some problems with getting reproducible results with the titration. These problems were likely due to human error in most cases. There were fewer complaints in the second year, possibly because a longer period of time was given for completion of the project (nearly the entire semester, as opposed to only six weeks) which allowed for more repeat trials.

Student work showed promise, but analysis was often too simplistic or relied on too few data points to draw a conclusion. This provided a good opportunity, however, to present important concepts such as estimating error and the need for a good experimental design with replication. In the second year, students were asked to lay out a detailed experimental plan for the data they would take to address their research question, and were given feedback on the appropriateness of their plan. In addition, preliminary reports provided more opportunity to give feedback on whether they were analyzing their data properly. Their oral presentations showed a good deal of sophistication, with all groups using PowerPoint presentations with imbedded graphics. It is obvious that they had previously given PowerPoint presentations in high school, as no time was spent teaching about the tool.

ASSESSMENT

Survey Results

A detailed survey was given to the students at the end of the semester to evaluate both the course in general and individual class activities. The results of this survey were used to assess the effectiveness of the hands-on CO_2 absorption experiment in educating freshmen about chemical engineering and increasing their enthusiasm for studying chemical engineering. Table 1 summarizes student responses.

As seen in this table, students generally felt that the CO_2 absorption activity improved their understanding of chemical engineering and increased their enthusiasm for studying chemical engineering. In addition, the CO_2 absorption activity was mentioned by 15 students (out of 36 students who responded) as one of the three most useful activities in the course (along with a field trip to a dairy processing facility and a lecture on biotechnology), and by 17 students as one of the three most enjoyable activities (along with the field trip to the dairy processing facility and a tour of the chemical engineering laboratories). It is interesting, but perhaps not surprising, that the most enjoyable activities had the students going out to see applications of chemical engineering or engaging in a hands-on activity rather than listening to a lecture.

TABLE 1
Assessment Results for CO_2 Absorption Activity

Aspect Assessed	Fall 2003	Fall 2004
Average response to: "This session improved my understanding of what chemical engineering is and what chemical engineers do."	4.07 (out of 5)	7.23 (out of 10)
Average response to: "This session increased my enthusiasm for studying chemical engineering."	3.64 (out of 5)	7.05 (out of 10)
Number of students listing the CO_2 activity in response to the following: "Of all the activities we did in class, which three did you find the most useful?"	N/A	15 (out of 36 respondents)
Number of students listing the CO_2 activity in response to the following: "Of all the activities we did in class, which three did you enjoy the most?"	N/A	17 (out of 36 respondents)

QUALITATIVE EVIDENCE

Most students seemed to enjoy the exercise. The opportunity to work with a "real world" engineering problem energized a number of the students. The students trying to evaluate the efficacy of the Fizzkeeper, for example, devoted a great deal of time (as well as a large amount of sealant products) to attempting to produce a bottle that would allow them to use the Fizzkeeper while simultaneously measuring the pressure in the head space of the bottle. It appeared that the students with a more applied, rather than theoretical, mindset appreciated the activity.

Student comments on the end-of-semester surveys were mostly positive, and also provide some insight into why students enjoyed the activity. Comments reflected the following positives about the activity:

1. *Provided an opportunity for a hands-on/laboratory activity*
2. *Allowed students to work in a group*
3. *Gave an idea as to what chemical engineers do*

The opportunity for students to work in groups was particularly well received. This was a great way for freshmen to get to know their colleagues, make friends, and form study groups for introductory science and engineering courses. Students were forced to work in groups to decide what experiments to run, to conduct those experiments, and to write the final report on the project, leading to closer interactions than what usually occur in a lecture course.

A few negative comments were noted. Comments in 2003 indicated that group dynamics were an issue. Some students felt as if they had done all the work while other students had done very little. To address these concerns, the next year more time was spent discussing group work, and peer review of group members was implemented. Another negative comment, noted in both years, was that the project goals were not well defined. This may, in part, be caused by the open-ended nature of how the project was implemented. Student groups were allowed to select their own projects with little input from the instructor. Perhaps more input is needed when the groups are selecting projects to ensure that the topic chosen will yield good results and that the groups properly define their objectives.

CONCLUSIONS

CO_2 absorption in carbonated beverages can be used as a hands-on activity in an introductory chemical engineering course to educate students on chemical engineering. This activity allows students to investigate a relatively familiar phenomenon, a carbonated beverage going flat, using engineering analysis. The CO_2 absorption activity was successfully implemented in a freshman introductory course at Kansas State University. Students responded positively to its impact on their understanding of and enthusiasm for studying chemical engineering. Most students also listed this activity as one of the most fun and useful activities in the course. Student comments indicated that they valued the hands-on nature of the activity and enjoyed working in groups on a significant "real world" engineering project.

REFERENCES

1. Unpublished data, based on comparison of enrollment of freshman chemical engineering students in the fall with enrollment of junior students in a class taught at the junior level two years later.
2. Seymour, E., "Revisiting the 'Problem Iceberg'—Science, Mathematics, and Engineering Students Still Chilled Out," *Journal of College Science Teaching* **24**, 392 (1995)
3. Hesketh, R.P., K. Jahan, T.R. Chandrupatla, R.A. Dusseau, C.S. Slater, and J.L. Schmalzel, "Multidisciplinary Experimental Experiences in the Freshman Clinic at Rowan University," *Proc. 1997 Ann. Conf. ASEE*, Seattle (1997)
4. Marchese, A.J., R.P. Hesketh, K. Jahan, T.R. Chandrupatla, R.A. Dusseau, C.S. Slater, and J.L. Schmalzel, "Design in the Rowan University Freshman Clinic," *Proc. 1997 Ann. Conf. of ASEE*, Seattle (1997)
5. Ramachandran, R.P., J.L. Schmalzel, and S. Mandayam, "Engineering Principles of an Electric Toothbrush," *Proc. 1999 Ann. Conf. ASEE*, Charlotte (1999)
6. Farrell, S., R.P. Hesketh, and M.J. Savelski, "A Respiration Experiment To Introduce ChE Principles," *Chem. Eng. Ed.*, **38**(3), 182 (2004)
7. Moor, S.S., E.P. Saliklis, S.R. Hummel, and Y.-C. Yu, "A Press RO System. An Interdisciplinary Reverse Osmosis Project for First-Year Engineering Students," *Chem. Eng. Ed.*, **37**(1), 38 (2003)
8. Henley, E.J., and J.D. Seader, *Equilibrium-Stage Separation Operations in Chemical Engineering*, John Wiley & Sons, New York (1981)
9. Crossno, S.K., L.H. Kalbus, and G.E. Kalbus, "Determination of Carbon Dioxide by Titration," *J. Chem. Ed.*, **73**, 175 (1996) ❐